


What is SOILS FOR EUROPE (SOLO)?

The goal of the Soils for Europe (SOLO) project is the identification of Knowledge Gaps related to increasing overall soil health across the EU. This includes the suggestion of actions related to Research and Innovation to fill these gaps, and also methods of evaluation and Key Performance Indicators to measure the impact of Research & Innovation. SOLO, a five-year project within the Soil Mission, features an iterative component, the Think Tank roadmap documents, which are built using a transdisciplinary and multi-actor approach that includes the co-creation and development of participatory methodologies to identify Knowledge Gaps, and their associated Bottlenecks and Actions. Each Think Tank aligns with of the Soil Mission objectives. A key element of SOLO is the active involvement of diverse stakeholders who collaborate and promote the exchange of knowledge throughout the project.

SOLO is designed in two conceptual directions: the "horizontal integration" of Research & Innovation priorities across the Soil Mission objectives, and a second related to the "vertical integration" of these same priorities across scales, from regions to the European level (Figure 1). While SOLO aims to develop knowledge-based Research & Innovation roadmaps for each Mission Soil objective, conflicting or competing priorities between these objectives may arise. Therefore, activities that traverse the project's roadmaps and the EU regions were established to allow SOLO to deliver a comprehensive synthesis of these priorities and identify these emerging patterns for both potential conflicts and synergies between Mission Soil objectives and their Research & Innovation priorities. This "horizontal integration" also allows for an increase in the interdisciplinarity of the roadmaps by engaging experts from different Think Tanks to exchange views and expertise. While the intent of this process is to develop a cohesive European-level roadmap for each Mission Soil objective, different regions in Europe will differ in their needs and priorities for research funding. To address this, SOLO will regionalize these roadmaps and highlight the different Research and Innovation needs to fill knowledge gaps to improve soil health across Europe. Activities of the vertical integration are Soil Week events that are organized in the member states of the 12 SOLO partners, and Regional Nodes that focus on specific regions and land uses in Sweden, Portugal, The Netherlands, and Hungary.

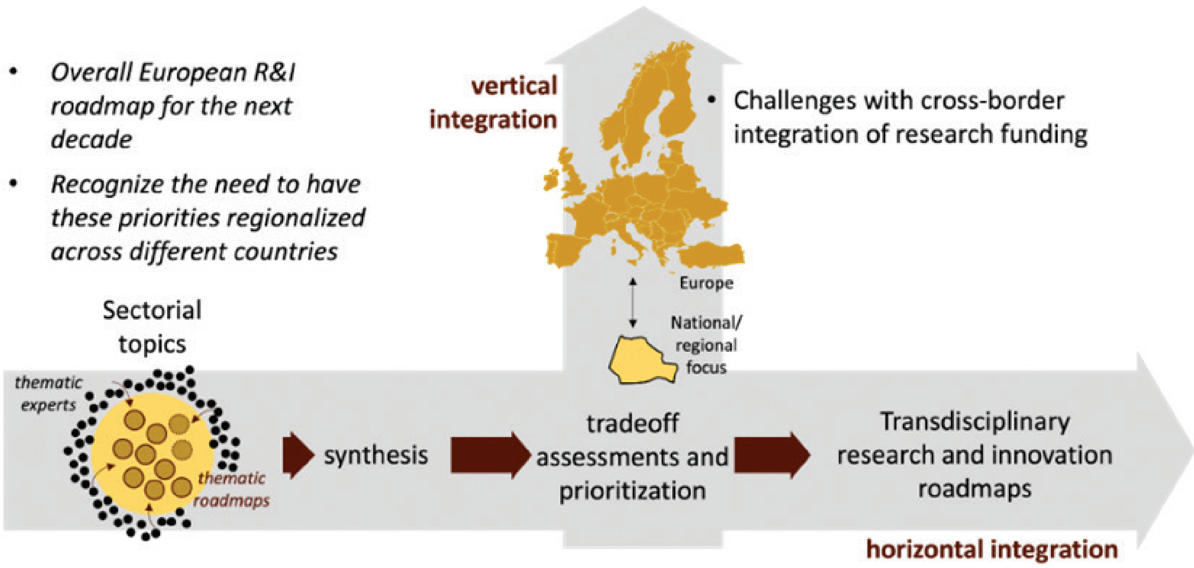

Figure 1. SOLO is conceptualized both horizontally, through development of Knowledge Gaps at the stakeholder level, though to a comprehensive synthesis, and vertically, by evaluating tradeoffs and priorities for different stakeholder groups, regions of the EU, and the EU as a whole. Sectorial (thematic) topics are based on the Soil Mission objectives and are on what roadmaps are based.

To facilitate roadmap creation and regionalisation, we identified the main drivers of soil health that serve as the knowledge base for discussions of the Think Tanks and the Regional Nodes, and we developed and participated in integration activities across Horizon projects (particularly the ones related to road-mapping activities). We also developed a shortlist of Key Performance Indicators that allow the Soil Mission to evaluate the efficacy and impact of resultant Research & Innovation activities and funding. Finally, we developed and implemented a communication and dissemination plan that includes a publishing platform that allows our outputs to undergo open review and be discussed by interested parties before publishing.

The organisation of SOLO

Nine Think Tanks comprise the expert Soils Network of Knowledge to address Research & Innovation priorities for the eight Soil Mission Objectives and the Nature Conservation of Soil Biodiversity:

- Reduce land degradation and desertification
- Conserve soil organic carbon stocks
- Stop soil sealing and increase re-use of urban soils
- Reduce soil pollution and enhance restoration
- Prevent soil erosion
- Improve soil structure to enhance soil biodiversity
- Reduce the EU global footprint on soils
- Improve soils literacy in society
- Nature conservation of soil biodiversity

The Think Tanks comprise groups of key stakeholders from diverse fields, expertise, and knowledge streams (Figure 2). These include a wide range of stakeholders from academia, public and private sectors, civil society, environmental organisations, and others.

Under a transdisciplinary approach, Think Tank leaders, along with key stakeholders have co-developed actionable roadmaps for soil Research & Innovation activities in the EU. Along with Knowledge Gaps, these roadmaps propose new research and research application avenues to constrain future challenges in maintaining and improving soil health. Roadmaps produced by each Think Tank are submitted for an open review process during which both invited and self-selected reviewers comment on content related to currently identified knowledge gaps, barriers, and

DOI: 10.5281/zenodo.17430539

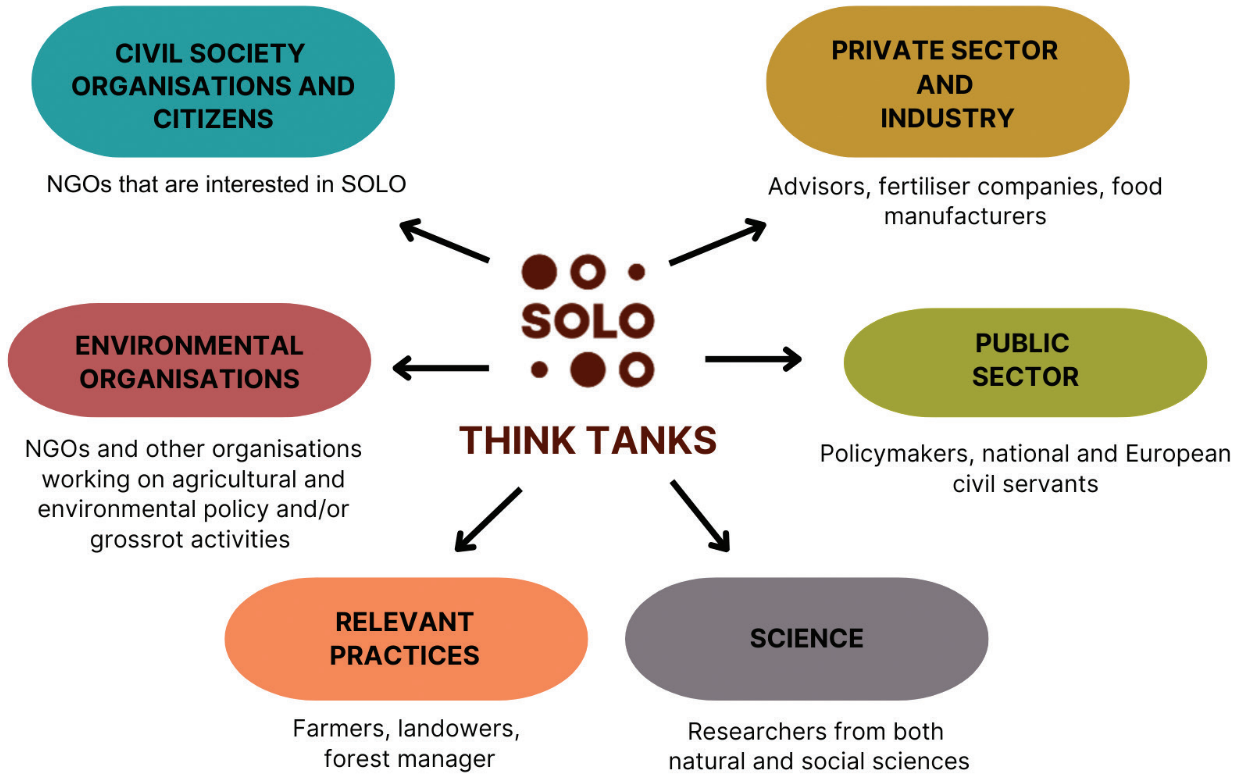

Figure 2. Key stakeholders targeted in SOLO.

actions to improve soil health. The Soil Network of Knowledge is essential for this annual review.

SOLO aims to develop a Soil Network of Knowledge. This is conceptualised as a wide network of stakeholders, including the participation of soil scientists, soil ecologists, social scientists and economists, anthropologists and psychologists, climate researchers, governance specialists, policy and lawmakers, NGOs, corporations, food quality and safety organisations, space agencies and Earth observation researchers, institutions related to impact assessment, restoration and remediation, consumer organisations, and educators. The Soil Network of Knowledge not only entails the co-creation procedures undertaken by the project's Think Tanks, but it also seeks to nurture collaboration among Think Tanks and other EU initiatives and projects. In other words, it aims at creating a community that expands beyond the project's immediate scope.

General methodology

Once launched, Think Tanks began to follow the steps of the engagement process. In this regard, a screening procedure was conducted, in which the Think Tank leaders identified key stakeholders taking into consideration their area of expertise and experience in relation to the specific Soil Mission Objective targeted by the Think Tank. An invitation was extended to potential stakeholders explaining the functioning of the Think Tanks and the project. Having initiated the Think Tanks, various participatory dynamics were implemented to co-define the Think Tank objectives, scope and limitations as well as the governance model. Incorporating stakeholders' input concerning all activities and incorporating feedback are actions undertaken in this procedure (Figure 3).

As mentioned before, SOLO is conceptualised as an iterative process (Figure 4). Therefore, actions and efforts carried out during the first year will take place annually, each year nourished by the knowledge generated during the previous one and, in its turn, nourishing the next. The roadmaps (which include the Knowledge Gaps presented in the different chapters of the "Outlook for Soil Health 2025") are further developed in annual in-person cross-fertilisation events. There, key stakeholders deliberate to refine the content of the roadmaps by addressing

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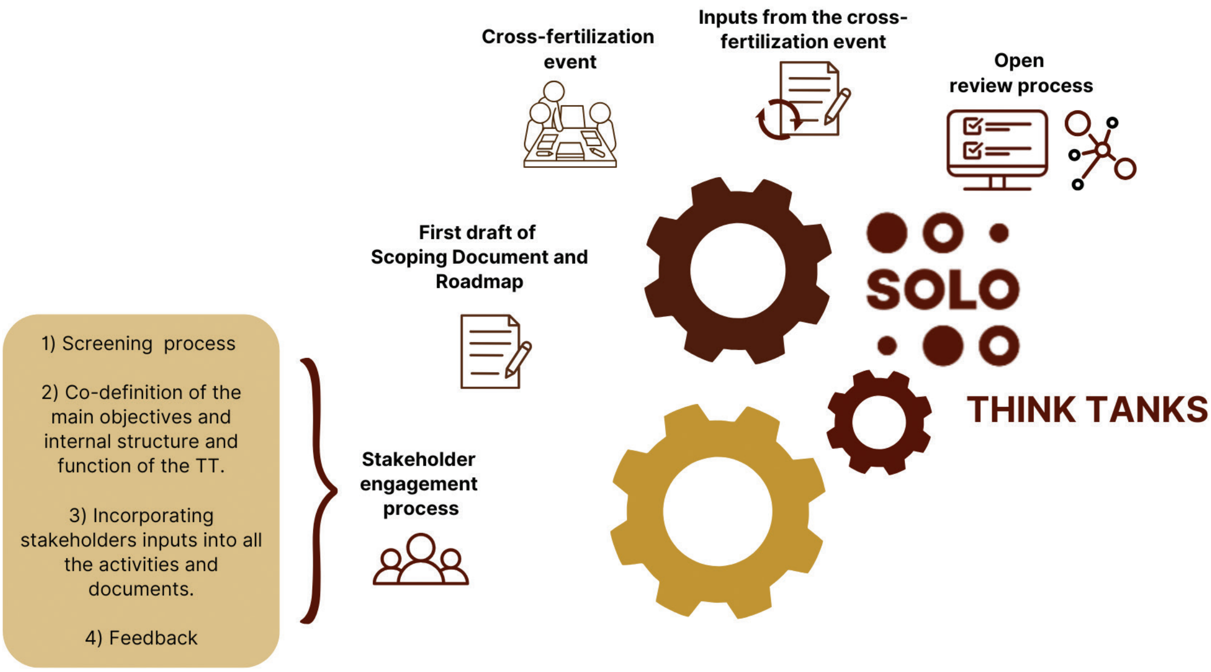

Figure 3. Soil Mission Think Tanks workflow.

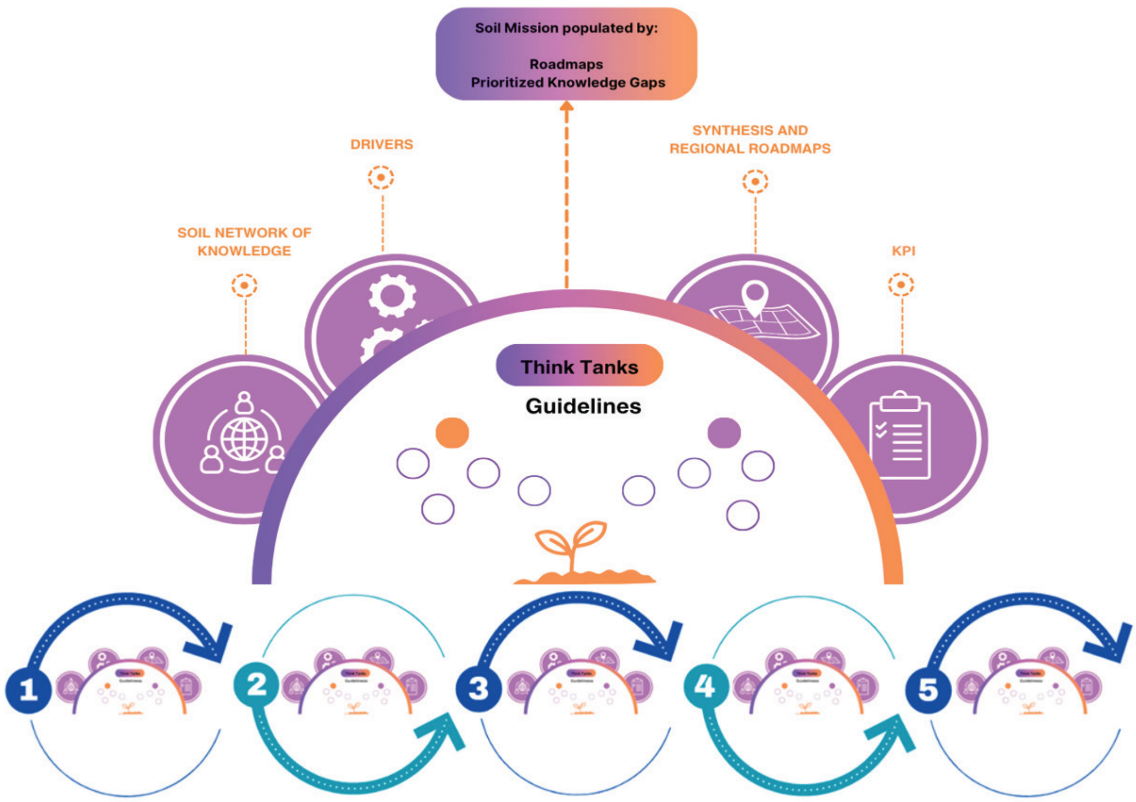

Figure 4. SOLO's iterative process.

knowledge gaps, proposed actions, and bottlenecks, and by setting priorities accordingly. These stakeholder events are essential to creating a collaborative space and engaging stakeholders in the process. All the inputs from these events, and additional online interactions, are integrated into the next iteration that will be in open review every year.

DOI: 10.5281/zenodo.17430539

Prioritisation methodology

For SOLO's main aim, delivering SMO, having the insight of all diverse expertise, knowledge and background involved in the decision-making process is key. Therefore, the importance of prioritisation together with the iterative nature of SOLO is an issue of concern for both the project consortia and stakeholders involved. In the first attempt to do so, in 2024, an exercise was planned and executed. This exercise was divided into two stages. First, stakeholders that attended the cross-fertilisation event in Sofia were able to participate casting their vote in person during the session dedicated to the prioritisation of the top ten knowledge gaps identified by each TT.

All top ten knowledge gaps of each TT were detailed in different sticky notes (except for the Footprints of soil TT that identified seven). These were put into the wall along with a sign that allowed them to identify which knowledge gaps referred to which TT. Then, the project coordinator explained that each person will be able to select three of the ten knowledge gaps per TT. To do this, circular stickers were provided so all the votes could be easily visualised after the exercise. Participants casted their votes simultaneously.

Furthermore, after the meeting in Sofia in November 2025, a second online exercise was conducted aiming at involving the stakeholders that could not attend the in-person meeting. For the project, it is pivotal to ensure the active participation of most stakeholders, especially in the decision-making processes. The objective of the online session was to replicate the procedure that took place in Sofia; hence, the same conditions and instructions were given. The voting was carried out through a Microsoft form allowing participants to select only three of the ten knowledge gaps per TT. After the voting exercise finished, TT leaders received the results so that they could share it with their respective stakeholders.

Finally, the votes gathered from the online session were added to the ones from the in-person exercise in Sofia to obtain the result of both exercises. This is the prioritisation that was embedded into the outlook chapters. Therefore, the top three knowledge gaps are extensively detailed in the document, meanwhile describing the remaining seven.

For the current iterative process (2025), the methodology to prioritise the knowledge gaps is yet to be refined if applicable. In this sense the selection of the method to be implemented is being discussed collectively among all the consortia partners. As mentioned, the iterative nature of SOLO coupled with the learning-by-doing reflexive process used is core in the project and therefore the prioritisation of the knowledge Gaps.

The Outlook for Soil Health

The actionable roadmaps of the nine SOLO Think Tanks are published as chapters in the Outlook for Soil Health 2025, and together contain the state-of-the-art information on knowledge and innovation needs of the EU to increase soil health. This publication represents the combined knowledge and expertise of the SOLO Think Tanks in identifying the Key Knowledge Gaps that need to be solved to move forward regarding each of the nine topics addressed by SOLO, the bottlenecks that have prevented filling these gaps in the past, and the resulting required actions. The Outlook is a comprehensive, but also living, document that will grow with further input by the stakeholder communities, the public, and the Soil Mission.

The Outlook for Soil Health 2025 also provides the basis for developing an overarching roadmap that concisely integrates the outputs of the SOLO Think Tanks, Regional Nodes and Soil Weeks. This overarching roadmap results from the horizontal integration across the thematic roadmaps of the Think Tanks, and the vertical integration by inputs from the Regional Nodes, Soil Weeks and, if applicable, other European projects (Figure 1). The core of the overarching roadmap will consist of the identified overarching themes of the key knowledge gaps, bottlenecks and actions, presented in quantitative tables. Furthermore, the links between knowledge gaps and associated bottlenecks and actions will be

DOI: 10.5281/zenodo.17430539

analysed, to identify leverage points in the transition towards increasing soil health in Europe. These analyses together will also demonstrate the synergies and trade-offs between the different mission objectives. The overarching roadmap for SOLO is updated and in open review in an iterative process.

Both the Outlook for Soil Health 2025, and the resulting overarching roadmap are intended as a resource for policy-makers, officials, and those interested in soil health priority-areas across the EU in developing an agenda for funding research and innovation initiatives that is tailored to current needs.

DOI: 10.5281/zenodo.17430539

Soils for Europe

SOLO

Outlook on the knowledge gaps to reduce land degradation in Europe

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1. Introduction

One of the primary processes jeopardizing soil health at a global scale is Land Degradation (LD). More precisely, according to the United Nations (UN), Land Degradation means „reduction or loss of biological or economic productivity and complexity of rainfed cropland, irrigated cropland, or range, pasture, forest, and woodlands resulting from land uses or a process or combination of processes, including processes arising from human activities and habitation patterns, such as: (i) soil erosion caused by wind and/or water; (ii) deterioration of the physical, chemical and biological or economic properties of soil; and, (iii) long-term loss of natural vegetation. Land degradation, therefore, includes processes that lead to surface salt accumulation and waterlogging associated with salt-affected areas.“ (United Nations 2007).

Notably, in the realm of soil conservation, there is often confusion between the terms soil degradation and land degradation, with soil erosion mistakenly considered synonymous with both. Furthermore, soil degradation encompasses more than just erosion, Soil degradation can involve: water erosion (includes sheet, rill and gully erosion); wind erosion; salinity (includes dryland, irrigation and urban salinity); loss of organic matter; fertility decline; soil acidity or alkalinity; structure decline (includes soil compaction and surface sealing); mass movement; and soil contamination (NSW Department of Planning, Industry and Environment, 2019). However, land degradation covers a broader scope beyond soil alone. Referring to its usage in land evaluation (FAO 1976), the term „land“ contains all natural resources contributing to agricultural production, including forestry and livestock production. This definition includes landforms, climate, water resources, soils, and vegetation (both forests and grasslands) (FAO 1999). Several interconnected components of land degradation exist, all of which may lead to a decrease in agricultural production (Douglas 1994), as cited by the Food and Agriculture Organization (FAO) (FAO 1999). Land degradation generally also includes processes other than soil degradation, such as alterations of superficial and groundwater resources, reduction of quantity and quality of plant production, biodiversity degradation (e.g. species extinction), or climate deterioration (FAO 1999).

In the context of the Soils for Europe (SOLO) project, and also in this Scoping Document, which aligns with the Soil Mission Implementation Plan of the EU, the term „Land Degradation“ primarily refers to “Soil Degradation”. This stems from the fact that according to the Soil Mission, the objective (Specific Objective 1) “Reduce Land degradation relating to desertification”, is linked solely to soil health indicators, such as soil organic carbon stock, presence of soil pollutants and excess of salts (European Commission 2019a).

The imperative to combat Land degradation on both European and global scales arises from the close association of Land Degradation with critical losses of biodiversity and key ecosystem services (Keesstra et al. 2018, Panagos and Katsoyiannis 2019). Furthermore, a substantial consensus within reports and assessments indicates that a significant segment of the Earth’s land surface faces degradation, estimated at between 20% and 40% of the total global land area (UN Convention to Combat Desertification 2019a, UN Economic and Social Council 2019, United Nations Convention to Combat Desertification 2022). In this light, according to Wischnewski 2015, 169 out of 194 countries, participating in the United Nations Convention to Combat Desertification (UNCCD), are affected by Land Degradation. Thenceforth, the degree of global land degradation today is considered to be negatively affecting 3.2 billion people worldwide (Brooks et al. 2006, Cardinale et al. 2012, Haddad et al. 2015, UNDP 2019, Panagos and Katsoyiannis 2019, Li et al. 2021).

As for the evolution of Land Degradation, it is essential to highlight that the Global Land Outlook report (United Nations Convention to Combat Desertification 2022) warns that without immediate actions, the problem of land degradation will persist and escalate. By the year 2050, if the current rates continue, an expanse equivalent in size to South America is projected to experience degradation (United Nations Convention to Combat Desertification 2022). Moreover, according to the Global Risk Report of the World Economic Forum 2025, natural resources shortages, including soil, represents the 4th most important long-term financial risk. This emphasizes the pressing need to address land degradation urgently in order to avert further environmental, economic and societal deterioration.

Specific concerns related to land degradation are also prominent within the European Union (EU). More precisely, data drawn from all EU Member States, as outlined in the Soil Mission Implementation Plan (European Commission

DOI: 10.5281/zenodo.17430539

2019a), highlight several alarming issues. Notably, it reveals that 83% of agricultural soils within the EU contain residual pesticides. In addition, a substantial number of potentially contaminated sites, amounting to 2.8 million, exist, with a mere 65,000 having undergone remediation efforts by 2018 (European Commission 2019a). Within the EU, issues related to soil erosion by water, compaction, soil sealing and excavation also persist. Approximately 24% of EU land is marked by unsustainable water erosion rates, 23% experiences compaction, soil sealing affected about 2.7 % of EU land, and a staggering 520 million tonnes of soil are excavated and treated as waste, despite the majority of it not being contaminated (European Commission 2019a). Relevant findings are also addressed in the recently published State of Soils for Europe report and the EUSO Soil Degradation Dashboard (European Comission and European Environment Agency 2024).

In addition, the aforementioned Soil Mission Implementation Plan (European Commission 2019a) underscores the pressing imperative to address land degradation and desertification*[1]. This urgency is reflected in the inclusion of the ‚Reduction of land degradation relating to desertification' within the Specific Objectives (more precisely, SO1) of the Soil Mission. In particular, the SO1 is intricately linked to the Mission's Target 1.1, which aims to ‚Halt desertification to help achieve land degradation neutrality and initiate restoration'—a commitment aligned with Sustainable Development Goal (SDG) target 15.3 (Combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation neutral world). The SO1 works as a catalyst for the attainment of other SDGs (European Commission 2006b, IPCC (Inter-Governmental Panel on Climate Change) 2001, United Nations Convention to Combat Desertification 2022), as well as key initiatives such as the EU Soil Strategy, the Green Deal, the Soil Monitoring Law, the 2030 Biodiversity Strategy, the Zero Pollution Action Plan, the Farm to Fork Strategy, the Circular Economy Action Plan, the Nature Restoration Law, and the EU Climate Law.

Mitigating land degradation necessitates a comprehensive approach encompassing sustainable land management practices, support to the farmers and land managers, multiple stakeholders working together, soil conservation, reforestation efforts, and initiatives to curb e.g., soil pollution and contamination. Moreover, despite the EU focus of the SOLO project, international collaboration, as exemplified by the UNCCD, also holds significant importance in tackling this challenge and safeguarding the integrity of our land resources for the benefit of future generations. The upcoming decades will be decisive in shaping and implementing a fresh and transformative EU and global land management and conservation strategy.

To support these efforts, the Land Degradation Think Tank forges a vibrant and transdisciplinary cluster through the active collaboration and engagement of key stakeholders and a diverse network of partners from various fields of knowledge, brought together by their commitment to soil health. This collaborative effort, along with an extensive literature review, aims to intricately weave together a roadmap that transcends traditional boundaries, seeking to pinpoint and address critical knowledge gaps, navigate through bottlenecks, and uncover cutting-edge technological innovations (Fig. 1). The ultimate goal is to craft a comprehensive strategy that effectively propels the mission to enhance soil health.

Thenceforth, the Land Degradation Think Tank's main objectives are to:

- Identify and enumerate key knowledge gaps related to land degradation in the EU, through a transdisciplinary approach.
- Identify and delineate drivers and obstacles (Bottlenecks) that hinder soil health in the EU.
- Identify the needs and priorities of the EU to achieve Land Degradation Neutrality by 2050.
- Identify and describe pioneering actions and activities that are crucial to overcoming the barriers that affect land health.
- Co-develop a research and innovation roadmap for the EU Soil Mission in relation to land degradation and integrate it into an overarching roadmap tackling the specific mission objective. Integral to this roadmap is the establishment of science-based guidelines

DOI: 10.5281/zenodo.17430539

Figure 1. Healthy soils connection to ecosystem services, contributing to the achievement of the SDGs and supporting the one health concept.

for defining threshold values for soil health, which will serve as critical benchmarks for monitoring progress, guiding restoration efforts, and fostering sustainable land management practices across the EU.

Given the above, the Land Degradation Think Tank adds value by uniting experts across disciplines to identify knowledge gaps, overcome obstacles, and co-develop a science/ stakeholders-based roadmap that guides EU efforts toward achieving land degradation neutrality by 2050 and improving soil health.

2. State-of-the-Art

2.1. Current state of the knowledge on Land Degradation

In the field of soil quality monitoring, the EU has adopted the definition of the FAO for Sustainable Soil Management (SSM) (FAO - ITPS 2020). According to the FAO, SSM includes the prevention, minimization, or combating of soil quality deteriorations which, in their extreme expression, might potentially lead to land degradation and desertification. At the same time, the United Nations Convention to Combat Desertification (UNCCD) has set a specific goal to achieve Land Degradation Neutrality (LDN) by 2030 (United Nations Convention to Combat Desertification 2017). In particular, the UNCCD's target is to stop the ongoing loss of healthy soils due to degradation, and promotes for the first time a two-pronged approach, with measures to prevent or reduce land degradation combined with other compensational measures for land degradation of the past. Implementing such effective measures requires a better understanding of Land Degradation drivers (e.g. aridity, unsustainable agricultural practices, forest fires, urbanization, mining and quarrying, drought), and processes (e.g. erosion, flooding, soil structure deterioration, pollution, soil sealing, compaction, loss of biodiversity).

Considering the paragraphs above, Land Degradation represents an essential „wicked problem" - a multifaced challenge - characterized by interconnected environmental, societal, economic and policy dimensions (Fig. 2).

Land Degradation poses significant challenges. Therefore, in recent decades, several

DOI: 10.5281/zenodo.17430539

SOILS FOR EUROPE

SOLO **Land degradation**

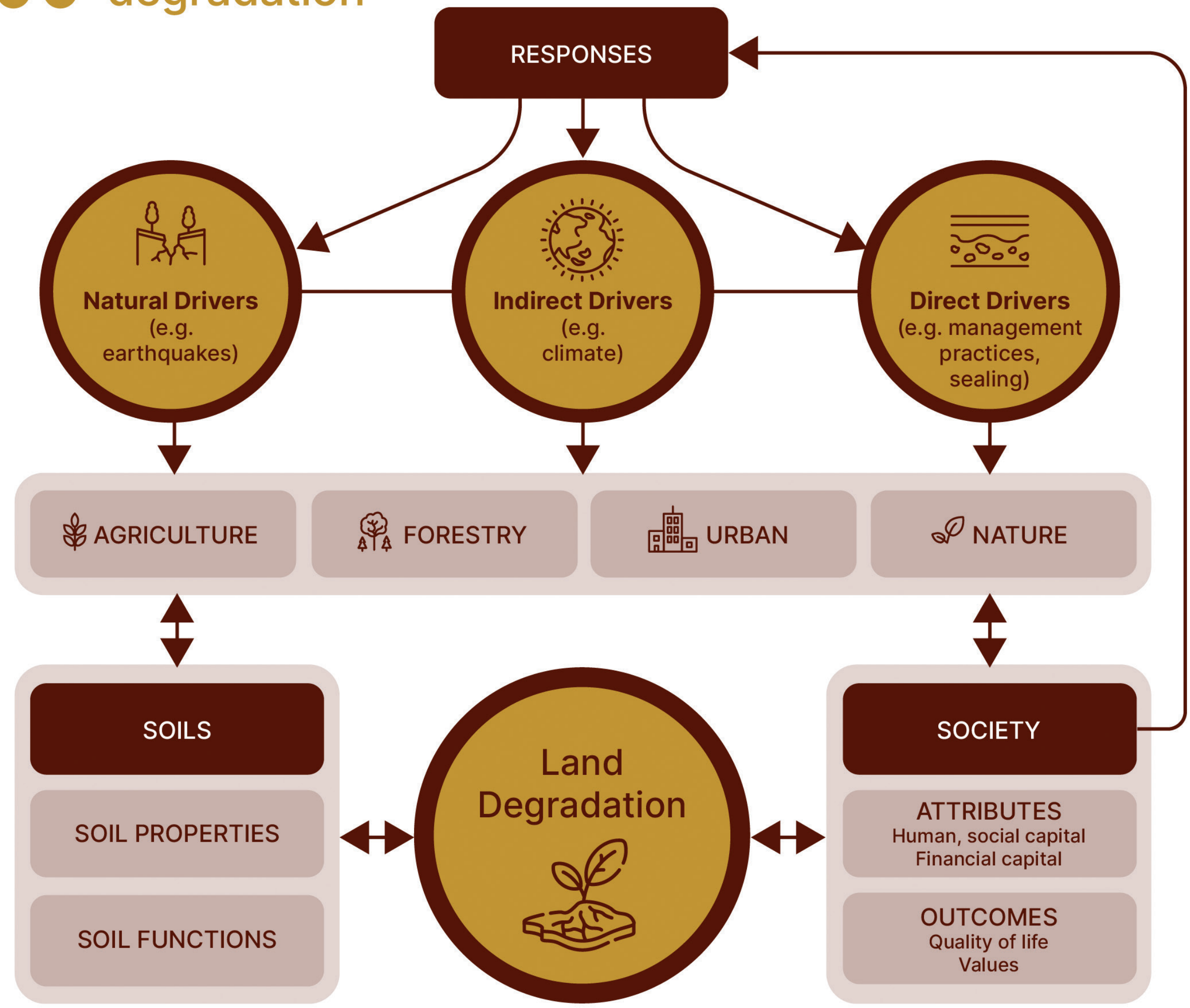

Figure 2. Land Degradation: A transdisciplinary challenge.

methods, approaches and datasets have been developed and used to assess the status of the complex and dynamic processes of Land Degradation in Europe, at different scales. More precisely, examples of datasets that provide information about Land Degradation components are the Soil Organic Carbon Dataset*[2] and the Salt Affected Soils Dataset*[3] of the FAO. The FAO also provides a plethora of relevant complementary datasets, such as the Map of Agreement on Global Cropland*[4] and networks. An example network refers to the Global Soil Laboratory Network (GLOSOLAN), established in 2017, and aims to enhance the capabilities of soil laboratories worldwide by standardizing analytical methods and data. This harmonization is essential to: i) Provide consistent and comparable information across countries and projects, ii) Facilitate the creation of unified soil datasets, and iii) Support informed decision-making for sustainable soil management.

Moreover, in 2023, the Joint Research Center's soil team (JRC D3), developed the EU Soil Observatory (EUSO) dashboard that integrates several soil related datasets. In particular, the EUSO Dashboard offers insights into potential locations (spatial resolution of 500 meters) of unhealthy soils within the EU, with plans for regular updates based on emerging scientific findings. As for the datasets that synthesize the EUSO Dashboard, they refer to but are not limited to erosion related datasets, such as the Soil Erosion by Water Dataset*[5] (based on the RUSLE

DOI: 10.5281/zenodo.17430539

model) and the Soil Erosion by Wind Dataset* [6] (based on the RWEQ model), soil pollution relevant datasets, e.g. the Copper Excess Dataset*[7] and the Mercury Excess Dataset* [8], and soil nutrient datasets, such as the Phosphorous Deficiency and the Phosphorous Excess Dataset*[9]. Additional datasets of the EUSO Dashboard refer to the Potential Threats to Soil Biodiversity Dataset*[10], the Soil Compaction Dataset*[11] and the Soil Sealing Dataset*[12].

Furthermore, over the recent decades, various concepts and methodologies have emerged to establish schemes for monitoring and assessing Land Degradation. More precisely, Gianoli et al. 2023, evaluated Land Degradation status at the EU level by applying the Convergence of Evidence (CoE) conceptual framework, originally developed for the World Atlas of Desertification (WAD), and incorporating additional indicators of land status and trends. CoE entails the idea that evidence from disparate and independent sources can converge to form robust conclusions (Gianoli et al. 2023). This conceptual framework has been employed in environmental science, particularly in conjunction with satellite remote sensing data (Cherlet et al. 2018, Ivits et al. 2013, Martínez-Valderrama et al. 2022). In the study by Gianoli et al. 2023 the additional indicators encompassed data such as population density and change, groundwater table decline, acidification, and eutrophication. These were complemented by variables aligned with those used in the WAD, such as soil erosion by water and wind, land cover, land productivity dynamics, baseline water stress, and biodiversity loss.

Similarly, another continental (EU-scale) study by Schillaci et al. 2022 evaluated the United Nations Sustainable Development Goal 15.3.1 indicator of Land Degradation across Europe. This study applied the UNCCD methodology and utilized the *Trends.Earth**[13] software, while also assessing the influence of alternative datasets, such as NDVI time series at varying spatial resolutions, alongside policy-relevant data sources for land cover (e.g., CORINE) and soil organic carbon (SOC) stocks (e.g., LUCAS dataset).

At the country scale, examples of applications employing the UNCCD approach, supplemented by Earth Observation (EO) and soil monitoring data, include the work of Wunder and Bodle 2019, who developed a land use change-based indicator for Germany. However, this approach may be affected by declines in land productivity (LP) due to decoupling strategies within the Common Agricultural Policy, such as reduced agricultural intensity (Schillaci et al. 2022). Another example is a high-resolution (20 m) assessment conducted for Italy, which incorporated additional variables, such as loss of habitat quality, burnt areas (2008–2018), and the density of artificial land cover (Assennato et al. 2020).

Despite these advancements, the baseline assessment procedure, as outlined in the UNCCD Good Practice Guidance (UNCCD 2021), faces challenges in some parts of the EU. These challenges include limited data availability due to small land-use parcel sizes, land suitability issues, resilience constraints, and socio-cultural and economic factors. As a result, monitoring land degradation using the three UNCCD land-based global indicators may lead to false positive classifications or an underestimation of the extent of degraded land (Schillaci et al. 2022).

In this light, assessing the indicator 15.3.1, which measures the proportion of degraded land over the total land area, necessitates ongoing data collection by countries to monitor changes spatially and temporally. Earth Observation can significantly contribute to both generating this indicator in countries lacking data and enhancing existing national data sources (Dubovyk 2017). To address this challenge, Giuliani et al. 2020 introduced an innovative, adaptable, and scalable approach for monitoring land degradation across different scales (national, regional, and global) by utilizing various components of the Global Earth Observation System of Systems (GEOSS) platform to harness Earth Observation resources for informing SDG 15.3.1. The proposed approach adheres to the Data-Information-Knowledge pattern, leveraging the Trends.Earth model (http://trends.earth) along with diverse data sources to compute the indicator (Giuliani et al. 2020).

Other essential examples of these concepts and approaches are the usage of the MEDALUS method, where the Climate Quality Index (CQI), the Soil Quality Index (SQI), the Vegetation Quality Index (VQI), the Management Quality Index

DOI: 10.5281/zenodo.17430539

(MQI) and the Social Quality Index (SoQI) were integrated under several climate change scenarios (Perović et al. 2021, Prăvălie et al. 2020). Besides, other components that describe Land Degradation in the literature refer to:

- Biophysical components (e.g. plant cover and agricultural productivity trends, net primary productivity, soil erosion etc.) (European Commission 2006aAyalew et al. 2020, Dubovyk 2017, European Commission 2006b, Panagos et al. 2020Giuliani et al. 2020, Jucker Riva et al. 2017),
- Environmental ClientEarth 2022, Gholizadeh et al. 2018, Giuliani et al. 2020, Gorji et al. 2019, Prăvălie et al. 2017, Taghadosi et al. 2019, Žížala et al. 2018) and/or
- Socio-economic factors (e.g. poverty, migration and population density) (Reed and Stringer 2016Akhtar-Schuster et al. 2017, Barbier and Hochard 2018, Keesstra et al. 2018European Commission 2020c, European Commission 2020b, Ustaoglu and Collier 2018Blaikie and Brookfield 2015, Istanbuly et al. 2022, Panagos et al. 2024, Sartori et al. 2019) as well as the
- Utilisation of long-term satellite observations (e.g. Sentinel-2 optical satellite constellation) (ClientEarth 2022, European Commission 2020c, United Nations 2023) which provide a practical way of generating a monitoring system that can derive cost effective and widely applicable indicators of Land Degradation.

In addition, Land Degradation is also assessed by fine-scale field-based and modeling techniques, Geographic Information Systems (GIS), informatics (Machine-Learning and Artificial Intelligence models), time-series and residual trends (European Commission 2020c, Žížala et al. 2018, European Commission 2020b, United Nations 2023, European Commission 2019b, European Commission 2021b, Dahal et al. 2024, European Commission 2021a, Gholizadeh et al. 2018, Perpiña Castillo et al. 2021, Xie et al. 2020, Petropoulou et al. 2023). However, throughout the lifespan of the Soils for Europe project, it is important to first clarify *what information* should be used to assess Land Degradation, rather than focusing on *how* this information is processed. By identifying the key data sources and indicators—such as soil health metrics, land cover changes, or productivity trends—a clear and consistent framework for soil degradation assessments can be established. Once the essential information is defined, then, the most effective methods (e.g., GIS, AI, or modeling techniques) to process and analyze this data can be explored. This approach could ensure a streamlined and actionable take-home message from the Land Degradation Think Tank to the relevant stakeholders, emphasizing the critical indicators to include in soil degradation assessments before delving into the technicalities of data processing.

Considering the above, it can be concluded that there have been significant advancements in scientific research, datasets, policies, and strategies aimed at addressing land degradation. Nevertheless, critical knowledge (application) gaps persist, hindering comprehensive solutions and effective knowledge transfer regarding this multifaceted issue. Land degradation is a complex, transitional problem with multiple drivers, scales, and perspectives, requiring integrated monitoring and assessment schemes (UN Convention to Combat Desertification 2019b, Reynolds et al. 2007, Vogt et al. 2011, Hessel et al. 2014, European Commission 2015, European Environment Agency 2019). While efforts have been made, challenges remain in understanding the full scope of land degradation, its drivers, and its socio-economic and ecological impacts.

For instance, while restorative practices like biochar and integrated nutrient management show promise, there is insufficient research on trade-offs, cost-effectiveness, and scalability across diverse land uses and pedo-climatic zones (Maroušek and Trakal 2022, Lal 2015, Keesstra et al. 2024). Additionally, gaps and limitations in data availability, quality and monitoring, along with the integration of cultural and socio-economic values into land management decisions further complicate efforts to achieve Land Degradation Neutrality (LDN) and understand LD effects and drivers (Dubovyk 2017, Jucker Riva et al. 2017, Žížala et al. 2018, Gholizadeh et al. 2018, Taghadosi et al. 2019, Giuliani et

DOI: 10.5281/zenodo.17430539

al. 2020, Ayalew et al. 2020, Bardgett et al. 2021, Jones et al. 2021, Silva et al. 2023). Thenceforth, the lack of comprehensive, standardized data and the underrepresentation of certain ecosystems, such as grasslands, mountainous regions, and urban soils, highlight the need for more inclusive and context-specific research (Löbmann et al. 2022, Chowdhury et al. 2024).

Moreover, while participatory approaches and stakeholder engagement are vital for sustainable land management, empirical evidence on their effectiveness and knowledge transfer remains controversial (Knierim et al. 2015, Löbmann et al. 2022). Economic assessments of land degradation and restoration efforts also face challenges, including inconsistent methodologies and the exclusion of non-monetary considerations, which hinder the development of robust, site-specific solutions (Panagos et al. 2018, Tepes et al. 2021).

In a nutshell, while progress has been made in understanding LD, the trajectory of future research must embrace a diverse array of topics, spanning from the exploration of the processes, mechanisms, and impacts of land degradation to the nuanced examination of the environmental, climatic, political, social, cultural and financial aspects of Land Degradation as driving forces behind its persistence (European Commission 2021c). Embracing cutting-edge technologies and monitoring methodologies, advancing theoretical frameworks, and refining ecological restoration approaches are imperative for fostering sustainable land management practices (European Commission 2021c). Moreover, interdisciplinary collaboration is essential for unraveling the complex dynamics inherent in land degradation phenomena and the formulation of robust policy frameworks is crucial to guide sustainable land management initiatives (European Commission 2021c).

2.2 Prioritization of knowledge gaps

The approach of the Land Degradation Think Tank (refer to Fig. 1) is designed to identify Knowledge Gaps, Actions, and Bottlenecks (see Section 3) throughout the SOLO project. Once a set of Knowledge Gaps was identified, the next step involved prioritizing these Knowledge Gaps to determine the most critical areas requiring research and funding within the EU.

The resulting prioritized (Top 10) Knowledge Gaps for the Land Degradation Think Tank can be found in Table 1 (Suppl. material 4) and are addressed in detail in Section 3.1. It is noteworthy that a complete list (and a short description) of all identified knowledge gaps is given in section 3.3.

3. Roadmap for the Land Degradation Think Tank

Despite the recent surge in scientific publications, policies, and strategies dedicated to addressing land degradation, it is widely recognized that significant knowledge gaps persist. Furthermore, even with maximum utilization of these various policies and strategies, it remains challenging to comprehensively address all aspects of land and its associated threats (European Commission 2022, Xie et al. 2020).

In this regard, the complex issue of Land Degradation needs a combination of the above-mentioned monitoring and assessment schemes (UN Convention to Combat Desertification 2019b) as Land Degradation is considered a complex issue with multiple dimensions, scales and perspectives, it is transitional and has multiple drivers and actors. This conclusion is also supported by other scientists such as Reynolds et al. 2007, Vogt et al. 2011, Hessel et al. 2014, European Commission 2015, and the European Environment Agency 2019.

Considering the above, it can be concluded that there are various knowledge gaps, and therefore, activities but also associated bottlenecks that should be considered regarding Land Degradation and the achievement of the aim of a LDN Europe in the upcoming years. These gaps highlight critical areas where research, innovation, and policy interventions are urgently needed.

The identified Knowledge Gaps are detailed in the following subsections:

- **Section 3.1** focuses on the **Key Knowledge Gaps**, which represent the top three priorities (Top 3 KGs) as outlined in Table 1.

DOI: 10.5281/zenodo.17430539

- **Section 3.2** covers the remaining prioritized Knowledge Gaps, ranked from the Top 4 to the Top 10.
- **Section 3.3** provides an overview of all identified Knowledge Gaps, Actions, and Bottlenecks, which collectively form the foundational elements of the Roadmap.

By organizing these elements into a structured framework, the Roadmap aims to provide a clear and actionable pathway for addressing Land Degradation and advancing toward LDN in Europe.

3.1 Key Knowledge Gaps

The **Key Knowledge Gaps**, representing the top three priorities as determined by stakeholder voting, are outlined below:

Knowledge Gap 1

Identification of the most efficient and cost-effective Land Degradation prevention and restoration measures, incorporating an assessment of trade-offs between different land uses and pedo-climatic zones.

As the EU grapples with soil degradation, scientists and practitioners have identified various land use and restoration measures to prevent and reverse degradation. These efforts span from traditional to modern knowledge and try to address the specific needs of different regions and land types. Among the promising restorative and sustainable practices are biochar (Maroušek and Trakal 2022, Kalu et al. 2022, Fišarová et al. 2024), organic matter, and nutrient-integrated management (Lal 2015, Keesstra et al. 2024). These measures are designed to minimize losses and maximize the efficiency of soil, water, and nutrient use, which is the guiding principle of achieving „more from less“ in land management (Lal 2015). However, much of the EU research funding and literature on sustainable land management (SLM) practices has predominantly focused on agricultural soils, with insufficient attention given to other land uses, such as urban soils or industrial and post-mining soils (e.g., Farrell et al. 2020, Table 1 of Löbmann et al. 2022, Psarraki et al. 2023, Figure 7 to 10 of Chowdhury et al. 2024, Zoka et al. 2024). Despite the growing work in land degradation prevention and restoration, challenges persist (European Commision 2020). Limited studies on trade-offs between different land uses and pedo-climatic zones, cost-benefit analyses, and the applicability of restoration techniques across various scales and socio-ecological contexts hinder the widespread adoption of effective solutions. As such, there is an urgent need for more comprehensive research that integrates diverse land uses, such as grasslands, urban areas, forested lands, and agricultural spaces, alongside other areas with various activities (industrial, mining, etc.). Some example studies that display such limitations can be found below:

Addressing Trade-offs in Restoration: Insights from Grassland Studies

A notable contribution to understanding these challenges is the study by Bardgett et al. 2021, which examined limited awareness and research on grassland degradation, at a global, and European scale. Their study emphasized the importance of grasslands in ecosystem functioning and biodiversity maintenance but pointed out that restoration efforts for these ecosystems remain underfunded and fragmented. Bardgett et al. 2021 applied a multi-criteria decision analysis (MCDA) model to identify sufficient solutions, addressing complex trade-offs among conservation practices (e.g. conventional and organic) and incorporating socio-economic factors, such as access rights and power dynamics between stakeholder groups (Martín-López et al. 2019). However, to achieve better outcomes from decision-making tools like MCDA, it is crucial to focus on the optimal allocation and prioritization of limited resources, especially since funding for grassland restoration is often scarce (Bardgett et al. 2021). In addition, they highlighted the necessity for new approaches that allow for the standardized assessment of grassland conditions,

DOI: 10.5281/zenodo.17430539

considering various environmental and climatic contexts. These approaches should evaluate the extent of grassland degradation, its impacts on biodiversity and ecosystem services, and the effectiveness of restoration initiatives. Moreover, the fragmentation of restoration efforts across regions and organizations further complicates these challenges, as data often remains incompatible or inaccessible, hindering knowledge sharing (Bardgett et al. 2021). Thus, the scaling up of restoration initiatives, particularly in grassland and other sensitive ecosystems, demands significantly more resources and concerted effort to maximize benefits and minimize trade-offs (IPBES 2018, Roe et al. 2021).

Cost-Effectiveness in Large-Scale Restoration: A Participatory Approach

Another example of innovative restoration planning is found in the study by Silva et al. 2023, who developed a participatory cost-effectiveness model to identify high-priority areas for landscape restoration. Their work, conducted in Southeastern Spain, a semi-arid region severely impacted by human activity, highlights the importance of considering both the financial costs and the potential improvements in ecosystem service delivery. The model they created not only accounts for the costs of restoration but also integrates stakeholder perspectives, offering a more holistic view of the restoration process. In their study, Silva et al. 2023 found that while restoration costs are generally lower than the costs of degradation, securing sufficient funding for restoration efforts in the short term remains a significant barrier. This underlines the importance of cost-optimization strategies and effective prioritization to make the most of available resources (Molin et al. 2018). The study also emphasized the need to improve the representativeness of stakeholder groups by including underrepresented sectors such as youth, women, and those with lower education levels (Silva et al. 2023). Such inclusiveness can help address imbalances in power dynamics and ensure that all perspectives are considered in decision-making processes. Furthermore, Silva et al. 2023 suggested that future restoration projects should focus on enhancing long-term stakeholder engagement through improved communication, clear modeling approaches, and real-time modeling tools that help stakeholders visualize restoration outcomes (Green et al. 2019, Hooftman et al. 2022). These measures would foster greater involvement in decision-making and ensure that restoration plans align with the needs of diverse communities.

In conclusion, achieving effective and cost-efficient land degradation prevention and restoration requires a multifaceted approach. While the application of restorative practices such as biochar and crop rotation show promise, scaling these efforts across diverse land types and regions presents considerable challenges. The integration of socio-economic factors, stakeholder engagement, and cost-effectiveness analysis tools, such as MCDA and participatory models, can help address these challenges.

Additionally, there is a need for standardized, European, national and local approaches to assess land degradation and guide restoration efforts, particularly in regions, where restoration is often underfunded. As research and case studies continue to evolve, it will be crucial to refine these strategies, improve stakeholder participation, and better understand the trade-offs of soil management practices between land uses and pedo-climatic zones.

Knowledge Gap 2

Lack of thorough understanding of the interactions between Land Degradation and Ecosystem Services. Land degradation continues to be a significant concern, with profound implications for ecosystems and the services (ES) they provide (Guerra et al. 2022). However, there are considerable knowledge gaps and limitations in understanding the interactions between land degradation and the delivery of ES. These gaps hinder effective policymaking and the development of sustainable management strategies. Some limitations that can be found in the literature are discussed below:

DOI: 10.5281/zenodo.17430539

To begin with, accurate and reliable data on land degradation and ES is crucial for understanding their interactions. Empirical evidence obtained through field and landscape indicators is vital for assessing soil health and the services provided by ecosystems (Petrosillo et al. 2023). However, the scarcity of region-specific measurements remains a significant barrier to advancing research in this field (Petrosillo et al. 2023). The lack of comprehensive and standardized data across different landscapes, combined with fragmented knowledge, often limits the ability to draw broad conclusions (Petrosillo et al. 2023). To effectively assess and monitor land degradation, there is a growing need for innovative tools and technologies. One of the most promising approaches is the use of remote sensing data, which can provide valuable insights into the type, extent, and severity of land degradation. By leveraging satellite imagery and aerial data, remote sensing allows for large-scale, precise monitoring of land conditions over time, enabling more accurate identification of degradation patterns. This technology plays a crucial role in understanding how land is changing and can guide targeted interventions to mitigate and reverse degradation (Prokop 2020, de Oliveira et al. 2022). However, challenges remain in integrating this data with on-the-ground field assessments (Prokop 2020, de Oliveira et al. 2022, Tziolas et al. 2024). Furthermore, despite the progress in using remote sensing for monitoring, the complexity of soil and ecosystem dynamics, including the role of soil biodiversity and its contribution to ES, remains insufficiently understood. More precisely, according to the study of Ferreira et al. 2022, associated with soil degradation in the Mediterranean region, local research has mapped soil heterogeneity and degradation through monitoring sites and long-term experiments at relatively small scales (e.g., Barão et al. 2019). However, this information is seldom collected or inventoried (FAO 2019). While all EU countries are required to produce state-of-the-environment reports, most Mediterranean countries do not regularly assess their soil resources (Solomun et al. 2020).

Moreover, one significant limitation in ES research is the difficulty in understanding, quantifying and integrating cultural ecosystem services (CES) into land management decisions. In particular, cultural services, including aesthetic, spiritual, and recreational values, are vital to human well-being but are often difficult to define and measure (Jones et al. 2021). This is primarily due to the challenge of understanding what motivates individuals to engage with nature and how these motivations relate to various cultural, social, economic, and psychological factors (Jones et al. 2021). In this light, several studies on soil degradation tend to focus predominantly on the natural dimensions, leaving insufficient attention to the cultural and social factors; however, a similar investment could lead to a similar degree of understanding.

To address these limitations, the study of Jones et al. 2021 proposed a framework that integrates cultural, social, and human capital, offering a promising approach to understanding the role of these factors in CES. While their trans-disciplinary study demonstrated that cultural capital, measured through EcoCentrism, was a strong predictor of environmental engagement, it also revealed that a significant portion of the variation in people's perceptions of natural spaces, such as urban meadows, remained unexplained. This points to a need for new metrics and frameworks that can capture the full range of motivations and values associated with cultural interactions with the environment. The incorporation of variables like intergenerational knowledge and indigenous relationships with land could further enrich this framework and provide a more nuanced understanding of CES (Jones et al. 2021).

Another study that investigated the research gap between soil biodiversity and the the delivery of soil ecosystem services, from Oberreich et al. 2024, with a focus on Germany, highlighted that soil and soil biodiversity are often overlooked in ecosystem assessments. Additionally, the social awareness of the term „ecosystem services" remains limited (Oberreich et al. 2024). Moreover, the findings suggest that the studies in the reviewed papers primarily focused on smaller spatial scales, emphasizing local and regional contexts. This is especially relevant for soil biodiversity, which, as the literature

DOI: 10.5281/zenodo.17430539

reviewed, varies due to several locally specific factors (e.g., Köhler et al. 2020).

Furthermore, land degradation and its impact on ES must be understood within broader socio-economic and policy contexts. While the role of soil-related ES in supporting human well-being is widely recognized, the interactions between ES and land use policies, particularly in terms of mitigating land degradation, need further exploration (Wei et al. 2018, Mengist et al. 2020). The principle of „Avoid > Reduce > Reverse" land degradation, which emphasizes avoiding further degradation as the most cost-effective strategy, is gaining traction in the context of land degradation neutrality (UNCCD 2017, Petrosillo et al. 2023). However, examples that depict a lack of policy integration in land degradation and ES research remain a major limitation. A notable example refers to the mountainous regions, where just a few studies link ecosystem service outcomes to actionable policy recommendations (Wei et al. 2018, Mengist et al. 2020). This gap in literature points to the need for more research on the role of policy in managing trade-offs and synergies between ES, land degradation, and human activities. In addition, there is a gap in research related to soil governance, particularly regarding the interactions between different governance mechanisms and their effects on soil management (Mason et al. 2023). This suggests a need for further exploration into institutions, policy support, and training in soil governance (Helming et al. 2018, Mason et al. 2023).

One other significant aspect is the valorization of ES which remains a significant barrier to understand the interactions between ecosystem services and land degradation. While valuable progress has been made in estimating the economic value of ES, particularly in the context of sustainable land management (SLM), the lack of reliable, comprehensive datasets hinders the full assessment of ecosystem service costs and benefits (Kieslich and Salles 2021, Mirici 2022). For instance, in landscape restoration projects, where benefits such as water regulation, drought resistance, and soil erosion control are critical, the incomplete data on these services, limits their effective inclusion in restoration planning (Almagro et al. 2013, de Groot et al. 2022). This data scarcity is a widespread issue in ecosystem and landscape restoration. However, two key initiatives— the TEER-initiative (The Economics of Ecosystem Restoration, led by FAO, CIFOR, and WRI) and the Ecosystem Services Valuation Database—may help address this issue (de Groot et al. 2022). Nevertheless, there still remains a pressing need for more accessible and reliable data to inform land management decisions.

Further research is needed to develop innovative methodologies, improve data collection and valuation practices, and strengthen the integration of policy recommendations into ES research. Addressing these gaps is essential for advancing sustainable land management practices and ensuring the effective delivery of ecosystem services in the face of land degradation.

Knowledge Gap 3

What are the historical, current, and future social and economic interactions with Land Degradation?

Land degradation presents significant challenges across multiple domains, including social and economic spheres. Understanding the intricate connections between land degradation, social vulnerability and structure, along with financial implications is critical to addressing its causes and impacts effectively. Although substantial research has been conducted on these topics, several knowledge gaps persist, particularly regarding the historical, current, and future socio-economic interactions with land degradation within the European Union (EU) (The Economics of Land Degradation 2015). Below, we separate the social and economic components of land degradation to highlight their respective limitations.

Social Impacts of Land Degradation

Land degradation directly affects communities, particularly in regions with intensive agricultural practices or vulnerable ecosystems. The social aspects of land degradation have been studied extensively, but several critical knowledge gaps remain. First, there is a need to understand the

DOI: 10.5281/zenodo.17430539

long-term societal consequences of land degradation (Johnson et al. 2024). Research has examined the immediate effects on agricultural productivity and rural livelihoods, but the total social cost, including health, migration, unemployment, inequality and displacement, is still poorly understood (Johnson et al. 2024). A key aspect is that land degradation can lead to social vulnerability by eroding community resilience and forcing vulnerable populations to migrate. Yet, the impacts of this environmental migration remain underexplored, with most studies focusing on climate change migration (IPBES 2018).

Second, there is a gap in understanding the role of indigenous and local knowledge in coping with land degradation. The integration of these traditional insights into modern land management practices could provide valuable solutions for more sustainable land recovery. Indigenous practices often emphasize ecosystem health and holistic land exploitation, offering an important counterpoint to contemporary methods of land degradation mitigation (Johnson et al. 2024). Yet, the validation and systematic integration of such knowledge remain insufficient and often overlooked in favor of purely scientific or technological solutions (Teuber et al. 2022).

Moreover, the socio-economic benefits of suitable land management practices have not been fully explored (examples were also discussed in the Knowledge Gap 1). Effective land restoration practices can yield long-term socio-economic returns, including improved food security, rural employment, and ecosystem services (Löbmann et al. 2022). However, a comprehensive understanding of how these practices contribute to community well-being, particularly in the context of varying socio-economic conditions across the EU, remains challenging (Visser et al. 2019, Amin et al. 2020, Löbmann et al. 2022). There is a need for integrated research to assess these benefits within diverse socio-economic contexts to facilitate the design of context-specific solutions.

Finally, the importance of participatory approaches in addressing land degradation has been recognized, particularly in the framework of the Agricultural Knowledge and Innovation System (AKIS), which fosters joint learning and co-creation (Knierim et al. 2015, Löbmann et al. 2022). Participatory approaches to data gathering and research, which engage farmers, amateur soil scientists, community members, or school students, have gained attention for both advancing scientific progress and achieving social and educational outcomes (Löbmann et al. 2022). As defined by von Korff et al. 2012, „participatory“ refers to the involvement of not only trained professionals but also a broader range of interested parties, including non-experts and local community members. However, there is a lack of empirical evidence on the effectiveness of these participatory approaches, which limits their potential to generate actionable insights (Hallinger and Nguyen 2020). Future research should explore the value of participatory methods in creating more inclusive, adaptive, and sustainable land management practices.

Economic Impacts of Land Degradation

According to the study by Panagos et al. 2018, 12 million hectares of agricultural land in the EU that are affected by severe soil erosion by water annually lose around 0.43% of their crop productivity, which translates to a cost of approximately €1.25 billion. The agricultural sector incurs a direct cost of €300 million, while the GDP loss amounts to €155 million. Italy is identified as the country with the highest economic impact, while most Northern and Central European countries experience only marginal losses Panagos et al. 2018. More recent and relevant financial information can be found in the State of Soils in Europe Report (European Comission and European Environment Agency 2024).

As seen from an economic perspective, the costs of land degradation and the financial viability of soil protection measures are critical areas where some knowledge gaps and limitations still exist. More precisely, land degradation has significant economic consequences, as in agriculture, which is often one of the most directly affected sectors. Despite this, there remains a lack of comprehensive economic assessments of soil protection practices, especially at the

DOI: 10.5281/zenodo.17430539

farm level (Tepes et al. 2021). For example, many existing studies on the cost-effectiveness of soil protection measures rely on secondary data and assume that the benefits of these practices consistently exceed their costs. However, this assumption is frequently challenged by evidence that indicates such benefits do not always outweigh the costs, especially in heterogeneous areas (Tim Chamen et al. 2015, Tepes et al. 2021).

Another major limitation in economic research on land degradation is the lack of consistent and comparable data. Much of the existing literature focuses on specific regions, using varied methodologies, and often excludes non-monetary considerations, which leads to gaps in understanding the full economic value of soil health (Kenter et al. 2016, Löbmann et al. 2022). For instance, many studies omit the broader economic implications of off-site impacts, such as soil erosion, which can have far-reaching effects on local economies, beyond just the immediate agricultural sector. These impacts are difficult to quantify and remain underexplored in many studies (Kubiszewski et al. 2013, Romanazzi et al. 2024).

Furthermore, economic models that assess the costs and benefits of land degradation and remediation often rely on overly simplified assumptions, such as the uniform distribution of soil degradation across different agricultural systems. These assumptions can lead to inaccurate estimations of the actual costs of land degradation. For example, studies conducted in regions like the UK and Germany suggest that economic outcomes can vary significantly depending on local agro-economic conditions, meaning that cost analyses should be conducted at more localized scales (Intergovernmental Panel on Climate Change 2019).

While progress has been made in understanding the social and economic dimensions of land degradation, significant gaps remain in both areas. From a social perspective, more research is needed on the long-term impacts of land degradation on communities, including migration, vulnerability, and the role of indigenous knowledge. A more integrated and participatory approach to land management is necessary to address the complex and context-specific nature of land degradation.

Economically, there is a need for more robust, site-specific studies on the costs and benefits of soil protection and remediation measures. Economic assessments should move beyond generalized assumptions and account for the diverse agro-economic conditions that influence land management decisions, while also accounting for off-site effects. Additionally, future research should explore innovative policy instruments that integrate both financial and social aspects of land degradation.

Ultimately, addressing these knowledge gaps will contribute to a more comprehensive understanding of land degradation, enabling the development of more effective policies and interventions. As the EU works toward its land degradation neutrality targets, these insights will be crucial in ensuring that both social and economic factors are accounted for in the sustainable management of land resources.

3.2 Prioritized Knowledge Gaps

As far as the remaining **Prioritized Knowledge Gaps** are concerned, they can be found below:

Knowledge Gap 4

Lack of comprehensive understanding of Land Degradation (effects and drivers)

There is a lack of comprehensive and detailed understanding of the causes, processes, and impacts of Land Degradation across different regions and soil types (Reynolds et al. 2007, Saljnikov et al. 2022, Daliakopoulos et al. 2016, FAO 2015, Ravi et al. 2010, Xie et al. 2020). Some relative examples refer to the difficulties that arise due to the diversity of perspectives on land degradation, limited studies regarding soil compaction, and complexities in revealing the intricate nature of interactions between Soil Organic Matter (SOM) fractions (Gianoli et al. 2023). More

DOI: 10.5281/zenodo.17430539

precisely, despite the existence of numerous case studies at a European and global level, applying such findings on a continental scale remains a challenge, as understanding the precise dynamics of driver interactions and their plausible impacts on specific sites requires detailed case-specific examination (Gianoli et al. 2023). Moreover, while there are some studies offering estimates of the areas affected by compaction, there are only a handful of field studies that actively monitor the impacts of soil compaction and the subsequent alterations in the soil structure and functions after a compaction event (Keller et al. 2017, Saljnikov et al. 2022). As for the gaps in understanding SOM fractions interactions, challenges can be found in understanding the relationships between aboveground and belowground biota (Orgiazzi and Panagos 2018), and the impact of drivers on the accumulation/decomposition of SOM (Jia et al. 2019). Consequently, more research is needed to fill these knowledge gaps and develop a better understanding of the complexities involved and the interlinkages between various drivers and processes concerning Land Degradation.

Knowledge Gap 5

How can we enhance regional planning regarding reducing Land Degradation?

One of the key challenges in enhancing regional planning to reduce land degradation is the fragmented nature of policies and the lack of coordination among various stakeholders (Saik et al. 2024). Research indicates that a unified political environment is essential for integrating LDN objectives across governance levels—from local to national authorities (Kust et al. 2017, Saik et al. 2024). Another limitation is the insufficient data on land resources and soil, which impedes accurate assessments of land degradation risks and restoration potential (Oliveira et al. 2018). To address these gaps, there is a need for improved data collection and monitoring mechanisms. Current research suggests that spatial planning tools and models, which assess land degradation risks and track restoration progress, could help align LDN efforts with broader climate resilience and economic development goals (Briassoulis 2019, UNCCD/Science-Policy Interface 2023). These tools are essential for developing integrated strategies that promote sustainable land management. Additionally, the integration of ecosystem services into land-use planning remains a significant challenge (Oliveira et al. 2018). While studies highlight the importance of incorporating ecosystem services into land management (Zhang et al. 2022), methods for assessing and quantifying these services in the context of LDN are still underdeveloped. Ecosystem services, such as soil fertility, water regulation, and carbon sequestration, must be accounted for in regional planning to ensure the sustainability of land-use decisions. As noted by Cowie et al. 2018, achieving LDN requires careful consideration of the balance between land degradation and restoration, which depends on reliable indicators for monitoring changes in land condition. Furthermore, a central knowledge gap in the current discourse is the lack of attention given to land degradation in strategic spatial planning (Oliveira et al. 2018). Although environmental issues are often acknowledged in land-use planning, few studies address how strategic spatial planning can effectively contribute to the reduction of land degradation, particularly in urban regions (Gomiero 2016, Albrechts 2016). As highlighted by recent reviews, strategic spatial planning has been increasingly recognized as an important way for managing land transformation, yet its potential to mitigate land degradation has not been fully explored (Briassoulis 2019, Cowie et al. 2019). In this context, there is a need to expand the role of strategic spatial planning in addressing land degradation. For regional planning to effectively contribute to land degradation reduction, it must move beyond the general recognition of environmental concerns and implement concrete strategies to protect and restore land (Oliveira et al. 2018). This requires the inclusion of all sectors of society, from land managers to local communities, in the planning process. Furthermore, it is essential that spatial plans are developed with clear objectives for sustainable land use and LDN implementation.

DOI: 10.5281/zenodo.17430539

Knowledge Gap 6

Lack of Land Degradation data and limited monitoring at different scales

Comprehensive data on land degradation (LD) is essential for understanding its causes, extent, and impacts, yet significant gaps exist across various spatial and temporal scales. Without accurate, high-resolution data on land and soil health, the development of targeted solutions and the implementation of effective policies remain a challenge (European Commission 2019a, European Commission 2020a, Saljnikov et al. 2022, United Nations to Combat Desertification 2016, Lunik 2022, Ontel et al. 2023). One notable example is highlighted by Panagos et al. 2020, where the uncertainty in soil erosion estimates arises from the lack of georeferenced data, specifically data on crop types and soil management practices implemented annually. This data gap makes it difficult to accurately assess the spatial distribution of land degradation and complicates the monitoring of restoration efforts.

Another example study that provides a flexible and valid starting point for assessing land degradation is not without its challenges (Manna et al. 2024). In particular, the study of Manna et al. 2024 highlighted that one of the significant issues is the difficulty of obtaining up-to-date databases for land cover and soil organic carbon (SOC) data. The lack of timely data can result in the underestimation of critical land degradation indicators, particularly in areas with irregular spatial distributions. These variations can often only be detected through in situ sampling or the use of very high-resolution multispectral images.

In addition to the technical limitations in data collection and analysis, there are conceptual challenges related to the measurement and classification of land degradation. A recurring issue in land degradation studies is the lack of clear differentiation between processes and drivers, cause and effect, as well as hazard and vulnerability (von Keyserlingk et al. 2023). This ambiguity complicates the development of quantitative risk projections and impedes the connection between research findings and decision-making processes (Akbari et al. 2016 Martínez-Valderrama et al. 2020b, Martínez-Valderrama et al. 2020a).

In many studies, land degradation is either treated as a permanent condition or as a discrete hazard, with limited consideration of its temporal dynamics. While some studies (Masoudi and Jokar 2018, Martínez-Valderrama et al. 2020) include probabilistic elements of risk, such as scenario analyses based on state and transition models, such approaches are not universally adopted (von Keyserlingk et al. 2023). The absence of a consistent framework for integrating temporal dynamics into land degradation assessments further limits the ability to predict future degradation trends and develop adaptive management strategies. Incorporating a more nuanced understanding of the processes, drivers, and risks associated with land degradation is essential to inform more effective policymaking and land management practices.

In conclusion, accurate data plays a pivotal role in several key processes related to land degradation, including monitoring and assessing land health, designing evidence-based policies, securing funding, and fostering collaboration among stakeholders. These processes rely on the availability of high-quality, comprehensive datasets. Therefore, it is crucial to prioritize data collection, the digital transformation of data systems, and dedicated research efforts aimed at addressing land degradation through enhanced research and innovation (R&I) initiatives.

Knowledge Gap 7

How do we support the farmers to make the turning point towards sustainable land and soil management soil practices?

Farmers often use management practices like ploughing, believing they will increase crop production. However, these practices can degrade soil and reduce yields in the long run (Quinton et al. 2022). Although several farmers recognize the challenges they face, they often lack the knowledge, means and/or motivation to

DOI: 10.5281/zenodo.17430539

adopt and implement sustainable practices and make the turning point towards sustainable soil practices. Tillage, common in crop production across 15.5 million km² of soil at a global scale, has been shown to cause soil thinning, reduce yields, and increase erosion, especially on sloping land (Quinton et al. 2022). Over time, mechanized farming accelerates this erosion, further diminishing productivity. To counteract these effects, adopting non-tillage practices is essential.

In addition, volatile agricultural markets can make it difficult for farmers to plan for the future. Access to accurate market data can help farmers make better decisions and improve profitability.

To support the transition to sustainable practices, farmers need better knowledge, training, funding and access to tools, such as reliable business models, that demonstrate the benefits of non-tillage, appropriate fertilization practices, and other sustainable farming methods. Consumers, on the other hand, need information (such as those recently developed for certified biodiversity-friendly practices: https://www.olivaresvivos.com/en/certification/) in order to compensate farmers and produce a better market value to support such practices. By addressing both the knowledge gaps and economic challenges, farmers can be empowered to adopt sustainable land management, benefiting soil health in the long term.

Utilizing the Voluntary Carbon Market to Enhance Liquidity in the Agri-Food Value Chain

One compelling approach to enhancing liquidity in the agri-food value chain is through the voluntary carbon market, which offers a financial incentive for farmers who adopt regenerative farming practices and provide ecosystem services to society. By sequestering carbon in soil and adopting nature-based solutions (NbS), farmers can generate high-quality carbon credits that can be sold in the market (Stofferis et al. 2025). As described in the Taskforce on Nature Markets (https://www.naturemarkets.net/), in addition to carbon credits, other types of credits are emerging, such as biodiversity credits and resilience credits. While carbon and resilience credits aim to bolster systems' ability to cope with climate impacts, biodiversity credits are specifically designed to protect and enhance biodiversity. These credits can complement each other within broader environmental and sustainability strategies. Resilience credits, in particular, monetize the benefits of risk reduction. They present a promising solution by providing a financial mechanism for investing in practices that enhance ecosystem resilience. The integration of resilience credits with insurance models could significantly boost global investments in NbS, offering a synergistic approach that combines financial risk management with ecological sustainability (https://www.nature.org/). Both resilience and nature-based carbon credits can play a crucial role in supporting adaptive management strategies in agriculture, helping farmers transition to sustainable practices while maintaining financial stability (Stofferis et al. 2025). Biodiversity credits, on the other hand, focus on conserving and restoring natural habitats, ensuring long-term ecological health. At this point in time, the voluntary market for carbon credits remains the most liquid. This liquidity provides farmers with an immediate financial return for their efforts in carbon sequestration, making it an attractive option. However, as markets for resilience and biodiversity credits develop, they too could offer substantial opportunities for farmers to gain financial rewards for their contributions to environmental health (Stofferis et al. 2025). Overall, leveraging these various credit systems can create a more sustainable and economically viable agricultural sector. By aligning financial incentives with environmental stewardship, we can ensure that farmers are rewarded for their role in enhancing ecosystem services, contributing to greater resilience and biodiversity, and ultimately supporting global sustainability goals.

Knowledge Gap 8

Limited mitigation Land Degradation strategies

There is a need for further research to optimize soil management practices, strategies and

DOI: 10.5281/zenodo.17430539

techniques that can help mitigate and prevent Land Degradation (Vanino et al. 2023). More emphasis should be placed on developing innovative and sustainable soil management practices that are suitable for different regions, scales and cases (European Commission 2020a, FAO 2015). In particular, there is a pressing demand for the establishment of systematic and validated methodologies to select/develop practices that will enhance our comprehension and facilitate the advancement and adoption of appropriate Sustainable Land Management (SLM) practices to diverse conditions (Giger et al. 2018, Gonzalez-Roglich et al. 2019, Liniger et al. 2019, Haregeweyn et al. 2023). In this regard, Liniger et al. 2019), highlighted the „insufficient attention to monitoring“ at the field level and identified the „involvement of land users“ in SLM and monitoring tasks as ongoing challenges. Demonstrating both on- and off-site impacts, as well as assessing both monetary and non-monetary „costs and benefits of SLM“ are essential to provide evidence for informed decision-making (Giger et al. 2018, Schwilch et al. 2014). Moreover, dissemination and training activities for the farmers are essential to support the application of sustainable soil management practices. More relevant studies are also discussed in Section 3.1 (Knowledge Gap 1).

Knowledge Gap 9

How do we educate and inform the population more effectively about the value of natural resources, including soil?

Effective education and engagement of the public on the value of natural resources, such as soil, is essential for achieving sustainable land management and environmental conservation. A key aspect of fostering this awareness is promoting meaningful dialogue between science, policy, and society. A notable example is the recent developments within the European Union (EU) that have highlighted the growing momentum involving citizens in biodiversity policy development. Initiatives like citizen science have been leveraged to encourage public participation, allowing citizens to contribute to knowledge production. At the EU level, online mechanisms have been employed to spread information and promote public deliberation, although participation remains inconsistent (Varumo et al. 2020). To strengthen this engagement, tools such as online science cafés have been explored in the study of Varumo et al. 2020, to facilitate dialogue between scientific communities, policymakers, and the public. These platforms are particularly valuable when addressing complex, multi-scalar challenges like soil degradation and natural resource management. Findings from research on such dialogues stress the importance of iterative communication processes that allow for continuous feedback and engagement (Varumo et al. 2020). This approach ensures that discussions are inclusive and that a diverse range of voices is heard, ultimately helping to inform and influence policy.

Moreover, to effectively address the environmental crisis, it is evident that neither traditional methods of education nor business-as-usual approaches are sufficient (Wals and Benavot 2017). Education for sustainability must be expansive and collaborative, involving multiple sectors, actors, and levels of governance. Schools and educational institutions must be integrated into their communities to influence not just students, but also decision-makers in government and business. This broader approach is critical for ensuring that long-term environmental concerns, such as soil health and natural resource preservation, are incorporated into decisions at all levels (Wals and Benavot 2017).

In summary, educating and informing the population about the value of natural resources like soil requires a shift toward more inclusive, participatory models of engagement. By incorporating iterative dialogues, fostering collaboration across sectors, and ensuring that sustainability education is embedded within communities, we can cultivate a more informed and proactive society that supports policies for the protection and sustainable use of natural resources.

DOI: 10.5281/zenodo.17430539

Knowledge Gap 10

Is the concept of Land Degradation Neutrality enough to ensure healthy land and soils in the future?

Land degradation remains a significant EU and global challenge, with far-reaching implications for agricultural productivity, ecosystem services, biodiversity, and human well-being. As soil health continues to decline, effective strategies are essential to address this pressing issue. One such strategy that has gained increasing attention is the concept of Land Degradation Neutrality (LDN), which has gradually materialized into concrete guidelines, thanks to the advice of the Science-Policy Interface of the UNCCD (United Nations Convention to Combat Desertification 2017, Cowie et al. 2018, Chasek et al. 2019). LDN promotes a balanced approach to land management, focusing on maintaining or restoring land productivity by integrating both degradation prevention and restoration efforts (Feng et al. 2022). By incorporating ecosystem services into land-use planning, LDN aims to safeguard natural capital and ensure long-term sustainability (Mikhailova et al. 2024). However, there is still a long way to go before LDN becomes an effective instrument. The proposal involves developing a plan that integrates the various sectoral plans already in place within each country, taking into account the National Irrigation Plans, the Forestry Plans, the Water Management Plans, the Strategic Plan for the Common Agricultural Policy, and several sectoral plans currently implemented at different administrative levels. Moreover, it is crucial to evaluate whether the concept of LDN alone is sufficient to ensure the health of land and soils in the future (Mikhailova et al. 2024).

For example, LDN analysis should not only be accomplished in an overall approach but also disaggregated by administrative units and LD type (e.g., agriculture) (Mikhailova et al. 2024). An overall LDN at the country or region scale can falsely imply overall LDN when there are ongoing LD increases in different types of LD (Mikhailova et al. 2024).

In addition, substantial challenges remain in translating LDN concepts into actionable strategies that effectively reduce land degradation at local and regional scales. One key challenge is the incorporation of LDN into land-use practices, particularly in regions with fragmented land ownership and insecure land tenure systems (Feng et al. 2022).

In Eastern Europe and Central Asia, for example, land reforms in the 1990s aimed at transitioning from centrally planned economies to market-driven systems (Sutton et al. 2016, FAO 2021). These reforms involved land restitution and distribution, resulting in a shift from large collective farms to individual family farms. While many of these countries have formalized land rights in registries, land fragmentation remains an issue in several European countries, often hindering agricultural productivity and contributing to unsustainable land management practices (Hartvigsen and Gorgan 2020). This fragmentation and insecure land tenure, particularly for women and girls, further exacerbate challenges related to land degradation (FAO 2021).

Furthermore, LDN must be integrated into broader land-use policies that consider both environmental and socio-economic factors to effectively ensure healthy land and soil for the future (Mikhailova et al. 2024). This integration could include estimates of the social costs of GHG emissions based on the concept of avoided vs. realized social costs (Mikhailova et al. 2024)

In conclusion, while the concept of Land Degradation Neutrality offers a promising framework for addressing land degradation, it is not sufficient by itself to guarantee healthy land and soil. Achieving sustainable land management requires a multi-faceted approach that includes addressing land tenure insecurity, land fragmentation, and incorporating social and financial dimensions into land-use planning. Moreover, continued research, data collection, systematic monitoring, and policy development are necessary to close the knowledge gaps and improve the effectiveness of LDN in combating land degradation globally.

DOI: 10.5281/zenodo.17430539

3.3 Overview

The subsection 3.3 displays three tables and one list of Knowledge Gaps. More precisely, Table 2 represents an overview of all identified Knowledge Gaps, Table 3 the Actions, and Table 4 the Bottlenecks, which collectively form the foundational elements of the Roadmap.

Lastly, a slightly more extensive description of the **Knowledge Gaps**, starting from number 11 onwards, is provided in the following paragraphs. These gaps, while not ranked among the top priorities, represent additional critical areas that require attention and further exploration to address Land Degradation effectively.

- **Current and future climate change interactions with Land Degradation in the EU:** Land Degradation and climate change are interconnected processes. However, there is still limited understanding of the exact interactions and feedback mechanisms between Land Degradation and climate change (European Commission 2015IPCC (Inter-Governmental Panel on Climate Change) 2001Intergovernmental Panel on Climate Change 2019, Odebiri et al. 2023). An example of some related knowledge gaps can be found in the following questions (Reed and Stringer 2016): Which variables play a crucial role in monitoring the interactions and feedback loops between climate change and land degradation? What role do climatic factors play in either mitigating or accelerating land degradation, and how can emerging opportunities be harnessed to achieve Land Degradation Neutrality (LDN) within the framework of a changing climate? What is the impact of Land Degradation on Climate? Furthermore, there is a strong focus on climate change on climate change impacts almost solely on agricultural crops and food production, overlooking livestock, forest farming and pests, as well as disregarding components of the food system and security (Farooq et al. 2022). As such, research is needed to assess the impacts of climate change on LD, as well as the potential of degraded land to contribute to climate change.
- **Current and future biodiversity loss interactions with Land Degradation in the EU:** Land Degradation and biodiversity loss are interlinked processes. Despite this fact, there are several limitations in understanding the causal relationships and feedback loops between biodiversity loss and land degradation. Examples of relevant knowledge gaps can be found in the effects of climate adaptation options on soil's role as a habitat and genetic reservoir. More precisely, according to the study of Hamidov et al. 2018, among the 20 EU case studies that they examined regarding the impacts of climate change adaption options on soil functions, solely a few consider the impacts on soil biodiversity. The evident neglect of soil biodiversity issues in the majority of case studies contradicts the growing recognition of the crucial functional role of soil organisms in soil processes (Cluzeau et al. 2012). This represents a significant knowledge gap that requires attention in future research endeavors (Hamidov et al. 2018). Additionally, there is a need for standardized, comprehensive approaches for measuring the compaction, diversity, and function of soil biota (Saljnikov et al. 2022, Thiele et al. 2020).
- **Absence of well-established and interlinked policies and legislations concerning Land Degradation and its components:** Lack of well-established and/or Land Degradation-related policy frameworks leads to unclear guidelines for soil management, resulting in a lack of standardisation in R&I methodologies (European Environment Agency 2019, Guerra et al. 2016). While this can be mainly seen as a bottleneck, it can also be characterised as a lack of knowledge when interlinkages between drivers affect the process of establishing clear policies. A relevant example refers to the study of Paleari 2017, where it was noted that despite the existence of several policies to address and regulate some soil threats, others, such as salinization, receive only limited consideration and lack a comprehensive framework for soil protection.

DOI: 10.5281/zenodo.17430539

- **Knowledge gaps on the quantification of off-site Land Degradation effects and costs:** The contemporary understanding of land degradation is marked by a significant gap in knowledge, particularly concerning the quantification of off-site effects and costs associated with Land Degradation (Boardman et al. 2019, Saljnikov et al. 2022). This refers to the impacts that extend beyond the immediate area of degradation and affect surrounding regions or ecosystems. The existing knowledge deficit in this specific aspect underscores the need for up-to-date research efforts to address and quantify these off-site effects and costs comprehensively.
- **Insufficient knowledge for accessing funds related to Land Degradation and soil projects and initiatives:** Insufficient knowledge to navigate the administrative procedures for accessing funds related to Land Degradation and soils (European Commission 2021c, EU Soil Observatory 2019). Are Land Degradation related funds and efforts sufficient to stop it?
- **Land Degradation models' limitations, uncertainties and capabilities:** Despite the existence of several models and methodologies to assess the Land Degradation status or components, there is a limitation in understanding their capabilities and uncertainties due to the lack of validation data and long-term measurements (Hessel et al. 2014Saljnikov et al. 2022, Aouragh et al. 2023, European Commission 2020a, Li et al. 2021, Prăvălie et al. 2021, Xu et al. 2023).
- **Lack of sufficient understanding of urban soils in relation to Land Degradation:** As indicated in the Soil Mission Implementation Plan (European Commission 2019a), the scope of land/soil degradation knowledge predominantly revolves around agricultural soils, with limited attention given to other land uses. It is necessary to bridge this gap and enhance our capabilities for supporting and rejuvenating land and soil health, both in urban and rural areas.
- **Difficulties in understanding the drivers of individual and collective decisions associated with Land Degradation:** Understanding the drivers behind individual and collective decisions is crucial for addressing land degradation effectively. Individual or collective decisions made by land users, such as farmers or landowners, play a significant role in shaping land management practices (Boardman and Evans 2019, European Commission 2019a, EU Soil Observatory 2019). Despite advancements in research, there are still difficulties in understanding individuals' decisions as decision-making is dynamic (it evolves over time in response to changing conditions), is represented by an inherent diversity (decision-making heterogeneity) and there is a lack of data to capture the behavioural factors (EJP Soil 2018).
- **Lack of understanding of subsurface processes related to Land Degradation:** The insufficient comprehension of subsurface processes associated with land/soil degradation underscores a notable gap in current research and data acquisition efforts. In comparison to topsoil, subsurface processes have not received a proportionate level of scrutiny. This incompatibility is further exacerbated by the fact that a predominant portion of existing Land Degradation and soil datasets (e.g. Soil Organic Carbon), as well as research projects and initiatives, predominantly concentrates on the topsoil layer (European Commission 2019a).
- **How can we sufficiently control water resources to avoid provoking issues in soils? How could the water directive be adjusted?** Water and land degradation are interconnected, with one often exacerbating the other. For example, deforestation can lead to increased soil erosion, which in turn reduces water infiltration and increases runoff, further accelerating land degradation (Borrelli et al. 2020). Water plays a significant role in land degradation, both as a cause and a consequence, as highlighted by the following key insights:

Water as a cause of land degradation:

Erosion: Water erosion is a major contributor to land degradation, particularly in areas with

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heavy rainfall, steep slopes, or poor vegetation cover. The force of moving water dislodges and carries away soil particles, leading to the loss of fertile topsoil and the formation of gullies and ravines (García-Ruiz et al. 2015).

Salinization: In arid and semi-arid regions, excessive irrigation can lead to the buildup of salts in the soil, making it unsuitable for plant growth. This process, known as salinization, is exacerbated by poor drainage and the use of saline water for irrigation (Mohanavelu et al. 2021).

Waterlogging: Over-irrigation or poor drainage can lead to waterlogging, where the soil becomes saturated with water, depriving plant roots of oxygen and causing their death (Ritzema et al. 2008).

Flooding: Floods can cause significant land degradation by eroding soil, depositing sediments, and damaging infrastructure (IPCC 2021).

Water as a consequence of land degradation:

Reduced water availability: Land degradation reduces the soil's ability to absorb and retain water, leading to decreased water availability for plants and humans (Lal 2015).

Increased runoff: Degraded land is less able to absorb rainfall, leading to increased runoff and a higher risk of floods (Montanarella et al. 2016).

Contamination of water resources: Land degradation can contaminate water resources with sediments, nutrients, and pesticides, harming aquatic ecosystems and human health (United Nations Convention to Combat Desertification 2022).

Despite the evident interlinkages between the two natural resources, current regulatory frameworks and policies often fail to address this nexus to and thence bridge soil and water resources management, perpetuating fragmented governance. An example is how disjointed policies fail to address feedback loops like salinization from poor irrigation practices.

- **How to ensure land restoration is an integral part of social structures and actions at all scales?** Engaging local communities and tapping into their traditional knowledge and innovations plays a vital role in achieving effective conservation endeavors (Economics of Land Degradation 2016). This principle aligns with the Aichi Biodiversity Target 8, which underscores the importance of respecting and leveraging traditional knowledge, innovations, and practices of indigenous people while involving local communities in conservation efforts (Convention of Biological Diversity (CBD) 2014). Their active participation not only ensures that they benefit from and are rewarded for their conservation efforts but also contributes to addressing land degradation. However, the limited capacity of local communities to address technical aspects of natural resource management poses a significant constraint that undermines SLM (Economics of Land Degradation 2016). More specifically, a challenge arises when attempting to integrate land restoration into social structures that drive social actions, particularly in the context of indigenous knowledge (Santini and Miquelajauregui 2022). In this light, despite the existence of studies exploring the benefits of indigenous knowledge in enhancing land restoration, involving local communities in restoration activities does not consistently result in successful ecosystem restoration or benefits for those communities (Tellez et al. 2019). Moreover, the social aspects related to land restoration are not thoroughly explored and there is not sufficient participation from local rural communities (Reyes-García et al. 2018, Van Noordwijk et al. 2020, Wehi and Lord 2017). There is still much work to be done in identifying the factors that contribute to successful restoration efforts that also bring advantages to local communities.
- **How to build commons-based land governance systems?** Contemplating land-based commons allows us to delve into the intricate dynamics of how individuals, communities, and humanity navigate interconnected natural and social environments (Giraud et al. 2016). From there, we can assess which organizational levels hold the greatest significance in understanding the interaction among customary, informal, and

DOI: 10.5281/zenodo.17430539

formal rules and practices. By incorporating these insights, we can craft adaptive approaches to natural resources management and delve into how territorial development strategies and organizational structures might impact the future of highly coveted land, such as arable and irrigable areas, as well as vulnerable territories like grazing and wildlife zones, forests, mountain tops, sacred sites, lakes and rivers - areas often targeted for land grabbing (International Land Coalition 2016). However, there are still existing challenges in establishing transparent and effective land governance systems (Giraud et al. 2016).

- **How do we shift from the current trend of intensification of agricultural production and overexploitation to land conservation?** More precisely, during the last decades, the EU has placed increasing demands on essential resources like food and fiber, necessitating a substantial boost in agricultural production. Modern agricultural technologies, such as machinery, fertilizers, and advanced irrigation, are crucial to meet this demand. However, large-scale construction and environmental challenges like climate change also stress European resources, particularly agricultural land (F.A.O. 2015). Soil, a non-renewable resource formed over millennia, is central to food, energy, and water security, as it supports over 95% of global food production (Saljnikov et al. 2022). Yet, the pursuit of higher agricultural output through technology can accelerate soil degradation to a critical point where further advancements can't compensate for inherent soil limitations (Saljnikov et al. 2022).
- **How can we support a land workers-led research on Land Degradation and how can we integrate the outputs of such endeavors?** Citizen science is an untapped resource for European soil and land research. In this light, the recent years the EU has been investing in a cornucopia of actions and projects to engage citizens in soil science and support them to preserve soil health (Panagos et al. 2024). Such actions and projects refer to but are not limited to the Soil funDamentals project, the UKSO Soil Observatory, the Grow observatory, the ECHO project, the Soil Plastics monitoring application, and the Heavy Metal City Zen project. Despite the significance and achievements of these efforts, there is a need to better communicate soil science to the plausible citizen scientists and a need to integrate the outputs of these projects (Wadoux and McBratney 2023).
- **How can we overcome the challenges in the land regulatory framework introduced by land ownerships?** As land is not a common good.
- **Lack of an early warning system related to soil degradation dynamics,** e.g. in case of a landslide (Dang et al. 2025, Yarahmadi et al. 2024).
- **Lack of knowledge on how to address the EU's competitiveness challenges in the global market.** These challenges include, but are not limited to, knowledge gaps in closing the European innovation gap—particularly in advancing the technology sector—and bridging the EU's financial shortfalls, as described in the Draghi report (European Commission 2024).
- **Lack of understanding Nature Based Solutions:** Not well studied yet (Dunlop et al. 2024).
- Is it possible to identify sets of adaptation options that complement each other, mitigating trade-offs and fostering mutually beneficial outcomes for both climate change and land degradation (Reed and Stringer 2016)?
- At what spatial scale do Land Degradation vulnerability maps offer the most valuable insights to decision-makers while maintaining a rich level of information and detail (Reed and Stringer 2016)?
- What resources are required for studying Land Degradation, and how do the monitoring (action) costs compare with the costs of not monitoring (inaction) across short, medium, and long time frames (Reed and Stringer 2016)?
- How do we pinpoint the thresholds, both in terms of time and space, at which Land

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Degradation adaptive practices and technologies may turn counterproductive, warranting discouragement of their widespread adoption (Reed and Stringer 2016)?

- What is the optimal resolution and frequency of monitoring to provide decision-makers with crucial information on key variables associated with climate change and land degradation (Reed and Stringer 2016)?
- How can we harmonize findings from monitoring both slow and fast Land Degradation-related variables (Reed and Stringer 2016)?

Acknowledgements

The Think Tank leaders would like to thank João Madeira, Saskia Keesstra, Guusje Koorneef, Robin Simpson, David S. Powlson, and Gondi Ferenc for sharing their valuable insights on land degradation, based on the initial version of our Scoping Document, during the SOLO project's physical meeting in Barcelona, Spain, from December 5-7, 2023. We would also like to express our gratitude to all the stakeholders who contributed their perspectives during various dissemination activities, as well as to all participants who helped shape the document during the second SOLO physical meeting in Sofia, Bulgaria, in November 2024.

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Endnotes

***1** Particularly as 25% of land in Eastern, Southern, and Central Europe faces the risk of desertification (European Commission 2019a).

***2** The dataset can be found at: http://54.229.242.119/GSOCmap/

***3** The dataset can be found at: http://54.229.242.119/GloSIS/

***4** The dataset can be found at: https://data.apps.fao.org/catalog/iso/c790f7c9-23ac-4578-b4bf-a8c0137f0fea

***5** The dataset can be found at: https://esdac.jrc.ec.europa.eu/content/soil-erosion-water-rusle2015

***6** The dataset can be found at: https://esdac.jrc.ec.europa.eu/content/Soil_erosion_by_wind

***7** The dataset can be found at: https://esdac.jrc.ec.europa.eu/content/copper-distribution-topsoils

***8** The dataset can be found at: https://esdac.jrc.ec.europa.eu/content/mercury-content-european-union-topsoil

***9** The dataset can be found at: https://esdac.jrc.ec.europa.eu/content/chemical-properties-european-scale-based-lucas-topsoil-data

***10** The dataset can be found at: https://esdac.jrc.ec.europa.eu/content/potential-threats-soil-biodiversity-europe

***11** The dataset can be found at: https://esdac.jrc.ec.europa.eu/content/natural-susceptibility-soil-compaction-europe

***12** The dataset can be found at: https://land.copernicus.eu/en/products/high-resolution-layer-impervious-built-up/impervious-built-up-2018

***13** For more information, please visit the following link: http://trends.earth/

DOI: 10.5281/zenodo.17430539

DOI: 10.5281/zenodo.17430539

Soils for Europe

Outlook on the knowledge gaps to conserve and increase soil organic carbon stocks

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1. Introduction to the Think Tank conserve and increase soil organic carbon stocks

More carbon resides in the soil than in the atmosphere and all plant life combined (Lal 2004). However, soils can act either as a carbon source or sink (Fig. 1), and currently represent a net source of greenhouse gas emissions in the EU, European Environmental Agency (EEA 2022). Thus, improved soil management geared at improving soil heath and reducing C losses could substantially contribute to achieving European Union climate targets. EU member states reported a total loss of 108 Mt CO_2 from cultivation and drainage of 17.8 Mha of organic soils in the year 2019, whereas only 44 Mt CO_2 were removed from the atmosphere by 387.6 Mha mineral soils (EEA 2022). In Europe and globally, peat soils contain the highest carbon stocks (Batjes 2002, De Vos et al. 2015) and it is essential to manage the water level of peat wetlands to maintain these stocks (Lloyd 2006). On average, global agricultural topsoil may have lost 2.5 ± 2.3 Mg C ha^{-1} (3.9 ± 5.4%) under constant net primary production (NPP). When accounting for NPP variations influenced by temperature and precipitation, the estimated loss is 1.6 ± 3.4 Mg C ha^{-1} (2.5 ± 5.5%) (Poeplau and Dechow 2023).

It is important to acknowledge that in addition to mineralisation, a significant loss of soil C happens by erosion and leaching (Chenu et al. 2019). Thus, the SOC stocks are a result of the simple balance of input and output with time as outlined in Equation 1:

$$dC/dt = I(t) - k(t)C \qquad \text{(eq. 1)}$$

where I is organic C input, k is the rate of C loss in the time-interval t.

The EU mission: a Soil Deal for Europe, defines “conserving soil organic carbon stocks” as one of the 8 mission objectives, addressing the importance of maintaining, or in many situations increasing the SOC stocks. As illustrated in figure 1, SOC is the main component of soil organic matter (SOM), mainly originating from plant debris accumulating and decaying in soil (Hoffland et al. 2020), slowly becoming a product dominated by molecules of microbial signature (Kallenbach et al. 2016), mixed and often adhering to soil minerals (Lehmann and Kleber 2015). A large body of previous research shows that the total input of organic C is a crucial factor in determining the long-term C stock, together with soil properties that control SOC stabilization (Mikutta et al. 2007, Schmidt et al. 2011). In 2017, the soil carbon “4 per mille 1000” initiative was launched to investigate the potential in increasing the soil organic matter stocks by 0.4%/year to compensate for anthropogenic release of greenhouse gasses (Minasny et al. 2017). This has fuelled an interesting debate on the complexity of soils, it's their use and quality in relation to carbon storage e.g (Moinet et al. 2022, Powlson and Galdos 2023, White et al. 2018). There is, however, an overwhelming body of evidence that

SOILS FOR EUROPE
SOLO Soil organic carbon stocks

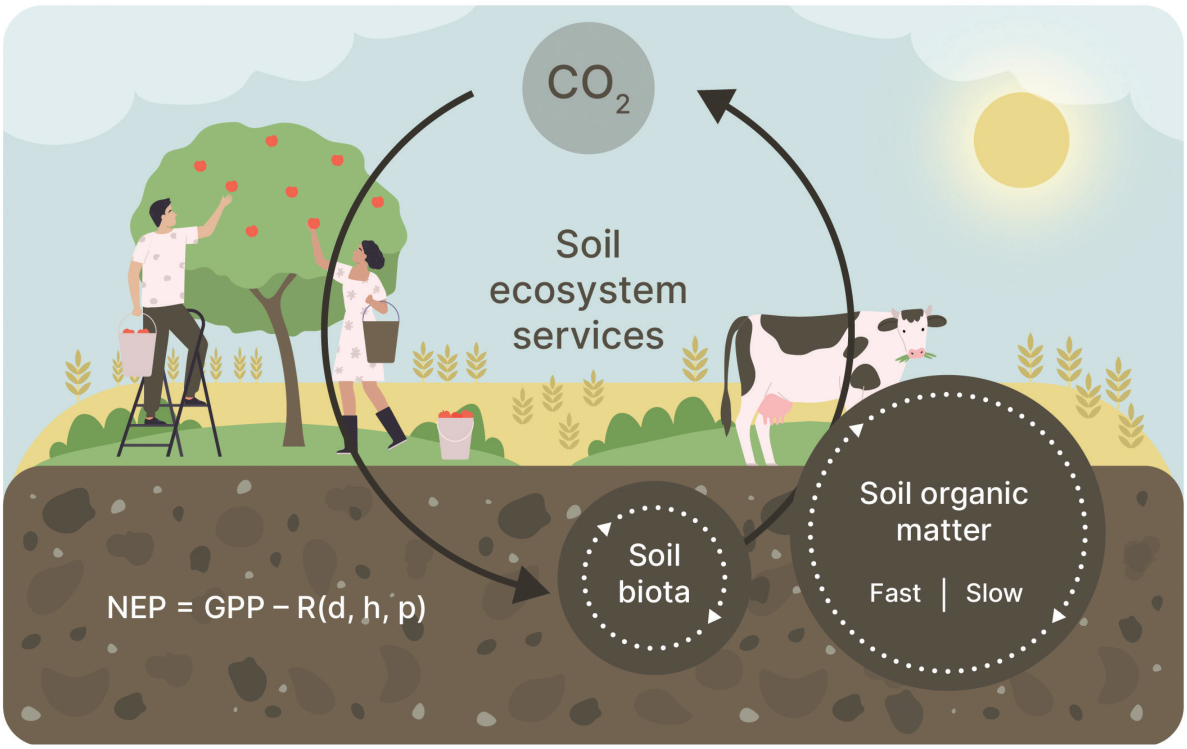

Figure 1. The figure illustrates how soil organic carbon (SOC) is a key component in the global carbon cycle. The flow of carbon (C) in the ecosystem is intricately linked to SOC stocks as fast and slow reacting soil organic matter. The C-flow play a crucial role in providing essential ecosystem services, acting as both a carbon sink and a source, depending on land use and management practices. The net ecosystem production (NEP) is a function of the gross primary production (GPP), respiration (R) by herbivores (h), plants (p), below- and above ground decomposers (d).

DOI: 10.5281/zenodo.17430539

increasing SOC stock in agricultural soils can help sustain or even improve biological, physical, and chemical soil properties, with benefits for soil organisms, root growth, as well as a range of other functions of soils important for many ecosystem services (Powlson and Galdos 2023). In cropland soils, the SOC stock is often declining, and vulnerable to further losses due to intensive management and climate change. Emphasizing the entire carbon cycle and the various functions of SOC, not just its stable forms, to better address climate mitigation and ecosystem functions, is essential for creating sustainable and resilient ecosystems (Janzen 2024). Conserving SOC in soils may support climate change adaptation, resistance and resilience to adverse weather conditions (Qiao et al. 2022), but it is challenging to combine global climate change mitigation and adaptation, through soil organic carbon sequestration while at the same time enhancing food security.

This soil mission objective aims at identifying actions that can limit the current carbon losses from cultivated soils and preferably reverse it to a rate of 0.1 - 0.4% increase per year (European Commission n.d.). The mission's objectives are relevant not only for supporting the aim to improve soil health by 2030, but also for the member states to become carbon neutral by 2050 (European Commission, n.d.). The SOC Think Tank addresses the importance of maintaining, or in many situations where possible increasing the soil organic carbon SOC stocks by:

- Addressing the impacts of management:
  - Climate change and adaptation technologies
  - Biodiversity and soil health
  - Forestry management
  - Agronomic and land use management
- Finding Technical solutions for monitoring, reporting and verification (MRVs):
  - Soil carbon measurement and monitoring
- Considering the socio-economic context:
  - Policy making and decision support
  - Urbanization and circular economy
  - Education and awareness raising
  - EU-footprints on SOC-stocks outside EU

2. State-of-the-Art

2.1 Current status of knowledge on conserving and increasing soil organic carbon stocks

Soil carbon stocks and quality are influenced by climate, soil minerals and aggregation (Lehmann and Kleber 2015), the rate of plant primary production, plant root interaction with soil and soil biology (Bai and Cotrufo 2022, Kätterer et al. 2011), and various management factors, such as land use, soil management and crop rotation (Cui et al. 2022, Fornara and Higgins 2022, Haddaway et al. 2017). A review of recent studies by Bai and Cotrufo (2022) highlights the essential role of management improvements, restoration and the capacity of plants and soil biology in controlling the formation of mineral associated organic material (MAOM) and particulate organic material (POM) promoting SOC storage, and thus mediating the impacts of climate change. The biogeochemistry of SOC is a dynamic continuum, ranging from intact plant residues to highly oxidized carbon in carboxylic acids. Understanding this continuum requires a mechanistic grasp of how SOC interacts with minerals, and how microbial activity mediates the balance between organic matter stocks and flows (Lehmann and Kleber 2015). Soil carbon is vastly heterogeneous, encompassing everything from last hour's root exudates to persistent humified material, millennia old (Amundson 2001). Soil organic matter is biologically most useful when it breaks down and releases plant nutrients, which is in direct contrast to the aim of storing more carbon in soils (Janzen 2006).

The EUSO soil health dashboard reveals that over 60% of EU soils are affected by one or more soil degradation processes or by soil sealing (EU comission 2023b), however gaps remain due to limited data on various soil degradation issues. Soil health is closely linked to SOC, as SOM affects soil structure, soil life and elemental cycles, which together sustain essential ecosystem functions such as erosion protection, soil

DOI: 10.5281/zenodo.17430539

biodiversity, primary production, climate regulation and water quality (Hoffland et al. 2020). The status of carbon quality, such as particulate and mineral associated fractions in relation to its stability and soil structure in agronomic and forests soils, has thus been a matter of intense research (Georgiou et al. 2022, Liang et al. 2017).

Increasing SOC stocks for climate change adaptation in Europe necessitates understanding the trade-offs and synergies of soil management strategies (SMS) and land use change (LUC) in relation to SOC stocks. This is closely linked to the concept of soil as a living ecosystem and the impact of biodiversity on SOC. Many lists of indicators for soil quality and soil health include carbon content and microbial respiration together because they are positively correlated (EU comission 2023a). This complex topic is influenced by various factors, including land use, environmental conditions, and biodiversity (Ratcliffe et al. 2017). Microbial biomass does provide ‚early warning' of slow changes in total SOC (Powlson et al. 1987). But biomass is not the easiest method for routine use. Alternatives exist; see Bongiorno et al. (2019). As microbial activity and nutrient release increase with increasing carbon content, nutrient mining may occur, potentially counteracting efforts to improve soil health Additional biological indicators may also provide insight about C dynamics and microbial activity (Liptzin et al. 2022).

Estimates of SOC stocks in Europe and globally are characterized by significant variability and complexity, influenced by factors such as initial SOC stock, climate, land use, and soil type. The initial SOC stocks are tightly related to SOC loss and initial SOC stocks explain the variability of the loss of SOC stocks globally (Poeplau and Dechow 2023). Soil organic carbon stocks in European agricultural soils are estimated at 17.63 Gt for the 0-30 cm depth, with regional variations due to climate and land use (Lugato et al. 2018). The average SOC stocks in forest floor soils has been estimated at 22.1 t C ha^{-1}, 108 t C ha^{-1} in mineral soils, and 578 t C ha^{-1} in peat soils, measured to a depth of 1 meter. In line with global trends observed in forest soils, the vertical distribution of SOC showed that approximately 50% of the carbon was concentrated in the top 20 cm, and about 55–65% was found within the top 30 cm of the soil profile (Vos et al. 2015). Soil organic carbon stocks and their distribution in the landscape are influenced by environmental factors such as climate, soil pH, and land cover type, which vary across Europe (Vos et al. 2015). This spatial variability necessitates region-specific models for accurate SOC estimation. Current estimates and models indicate both challenges and opportunities for SOC management, highlighting the need for further research to refine these estimates to reduce uncertainties, and support effective policymaking for carbon sequestration and soil management in general.

Integrating soil monitoring frameworks with natural capital accounting can improve assessments of soil conditions and changes, supporting policy and socio-economic decisions. While public awareness of the importance of soil health, soil carbon, and climate change is growing in Europe, significant gaps and challenges remain (Thorsøe et al. 2023). Enhancing knowledge transfer and increasing public engagement are essential. Key recommendations include strengthening knowledge brokers, making research more applicable to practitioners, and providing incentives for sustainable land management.

Changes in soil carbon stocks occur slowly, with management effects varying across climate zones and soil types. Effective implementation of soil carbon management technologies necessitates interaction with all relevant stakeholders, including farmers and landowners, agronomic advisors, agricultural supply companies, policymakers, and those involved in the food supply chain. Practitioners possess essential knowledge and experience about their own land, and mutual knowledge exchange will facilitate the necessary engagement for innovative technology implementation, ultimately improving soil carbon stocks and overall soil health.

In general, there is a need for more knowledge on long-term trends in European cultivated and non-cultivated soils (such as forests, peat, pasture, natural grass and heath lands) and documentation on consequences of land use changes, impacts of urbanization and new technologies on soil properties and soil organic carbon stores.

This is best achieved by a combination of:

DOI: 10.5281/zenodo.17430539

1. detailed studies to investigate mechanisms of C turnover and stabilization
2. continued interpretation and re-interpretation of data from long-term experiments
3. surveys of organic C changes in realistic on-farm situations
4. interaction between policy makers and relevant stakeholders

2.2 Prioritizations of knowledge gaps

The SOC Think Tank has examined the state of the art and identified knowledge gaps regarding the impact of agricultural and forest land uses on SOC. It also explored how biodiversity, the circular economy, and urbanization interact with SOC stocks. Additionally, the need for further research and implementation in modelling and method standardization was highlighted. The investigation extended to identifying how SOC is affected by EU policies outside the EU and addressing literacy gaps in this context. Numerous knowledge gaps were identified for each topic. Despite this, several gaps can be grouped and prioritized, while still validating the identified research and innovation development and application gaps. The preliminary identification of all knowledge gaps was published in the Almås et al. (2024) scoping document.

Before the stakeholder workshop organized by the SOLO team in Sofia on November 5th and 6th, 2024, the SOC Think Tank key stakeholders identified the most critical knowledge gaps for each of the aforementioned topics affecting SOC stocks. Based on this pre-identification, Think Tank members grouped and reported the ten most essential and comprehensive knowledge gaps for further prioritization at the Sofia workshop. The key knowledge gaps that received the highest scores defined a preliminary ranking. This process was later repeated with a larger group of stakeholders in an online meeting. The cumulative scores resulted in the ranking identified in Table 1 below. The final list was also presented and verified by participants of the “soil pollution and restoration” Think Tank „Soil-week“ event held in Hungary on December 4th.

Table 1. Ranking of the top 10 knowledge gaps identified (a full list of all identified knowledge gaps is available under Suppl. material 1. *KDG = knowledge development gap, KAG = knowledge application gap*).

Rank	Knowledge gap	Type of knowledge gap
1	Increasing SOC stocks for climate change adaptation	KDG
2	Biodiversity; interaction between soil carbon and soil biology	KDG
3	Policy making and decision support	KAG
4	Soil carbon monitoring, reporting and verification (MRV)	KDG
5	SOC and circular economy, LCA	KDG
6	SOC in agronomic systems	KDG
7	Urbanization and SOC	KAG
8	Education and awareness raising on SOC	KAG
9	Management of forests and SOC	KDG
10	EU footprints of soil carbon outside Europe	KAG

3. Roadmap for the topic “Conserving and increasing soil organic carbon stocks”

3.1 Key knowledge gaps

An overview of the prioritized knowledge gaps, their sector impact, bottlenecks and suggested actions are summarised in Table 2 (Suppl. material 1) in the end of Chapter 3.

Knowledge gap 1: Increase SOC stocks for climate change adaptation

The investigation has identified the following knowledge development gap:

The knowledge gaps to increase SOC stocks for climate change adaptation requires a broad and interdisciplinary field of research, involving various disciplines, methods, and perspectives

DOI: 10.5281/zenodo.17430539

concerning soil health, quantification of SOC stocks, regional variability, mitigation strategies and integration with agricultural policies. This knowledge gap represents several topics requiring knowledge development for further research and innovation actions.

Many European soils are degraded, necessitating the development of specific indicators that correlate with SOC storage and climate resilience. Monitoring and assessing SOC stocks across diverse landscapes is challenging due to inconsistent data and methodologies. Integrating SOC considerations into agricultural policies and fostering collaboration among policymakers, scientists, and practitioners is crucial. Additionally, understanding the effects of climate adaptation measures and forest management practices on SOC, and providing incentives for farmers and forest owners to adopt sustainable strategies, is important.

The management of soil should focus on sustainability of food and fibere production and sustaining ecosystem services. This puts climate change adaptation as the primary aim for soil management rather than mitigation. The impact of climate change on food and fibere production depends on the responses and adaptations of farmers, consumers, markets, and policies. These adaptations are the result of complex optimization decisions and general equilibrium dynamics, and thus difficult to measure and predict (Page et al. 2020). Increased SOC stocks generally favour both mitigation and adaptation as higher SOC in top layers in e.g. no tillage systems, provide resilience to extreme weather conditions (Haddaway et al. 2017).

Climate change adaptation includes soil and crop management practices for soil water retention and effective water infiltration strategies, which both are closely linked to maintaining or increasing SOC stocks. Practices such as organic amendments and maintaining continuous living cover improve soil structure, by improving soil aggregation and enhancing bio-porosity. Bio-porosity refers to the presence of pores in the soil that are created or enhanced by biological activity, such as the action of soil organisms like earthworms. This enhances water infiltration and reduces surface runoff, although bypass flow through biopores may increase nutrient losses (Sims et al. 1998). However, these can also reduce soil water storage and groundwater recharge, particularly in dry climates: In Mediterranean rainfed agroecosystems, techniques like no or minimum tillage, and direct drilling improve soil water retention and potentially carbon storage in top mineral soils (Blanchy et al. 2023). But the potential in climate change mitigation is limited considering the whole soil profile (Cai et al. 2022), acting as both adaptation and mitigation strategies, and results from cool and humid climate are not so promising (Honkanen et al. 2024). The choice of tillage and residue management significantly affects SOC dynamics. Retaining crop residues can mitigate SOC losses, while residue harvesting leads to substantial declines (Herzfeld et al. 2021).

Soil organic carbon stocks are influenced by climate and land use changes, and in Mediterranean areas, conversion from natural vegetation to agriculture significantly reduces SOC stocks (Lozano-García et al. 2017). Other studies have shown the same, and generally the loss of SOC is strongest when turning grassland and forest into cropland (De Rosa et al. 2024, Poeplau and Don 2013). According to the study by Poeplau and Don (2013) the land use change from cropland to forest increased SOC by 21 Mg ha^{-1}, while grassland to cropland decreased SOC by 19 Mg ha^{-1}. Across Europe, SOC stocks may increase by 2050 under various climate and land cover scenarios, although the extent varies (Yigini and Panagos 2016). The effectiveness of these strategies can vary based on local conditions and requires careful consideration of trade- offs.

Farming systems with focus on soil management, e.g. practicing reduced or no tillage to achieve minimal soil disturbance, as well as crop rotation, cover crops, and plant residue or manure return. Such practices will have impacts on SOC storage, thus contributing to climate change mitigation and adaptation.

Organic farming has the potential to increase SOC stocks and sequestration rates (Clark and Tilman 2017), and can offer larger environmental benefits in comparison to conventional agricultural systems (Gattinger et al. 2012). However, organic farming generally pro-

DOI: 10.5281/zenodo.17430539

duce slightly less biomass, and the effect on soil carbon stock from organic farming is complex and content performance dependent (e.g. climate, soil characteristics etc, Seufert and Ramankutty (2017)). Organic farming is, in principle, based on fertile soil that must be maintained through regular application of organic material as fertiliser. Over time, this has the potential to also increase SOC. Organic farming may in some cases also involve reduced tillage, although soil tillage is often used for weed control. Reduced tillage has the potential to increase total SOC stocks, if crop management is optimized. Krauss et al. (2022) reported the effect of reduced tillage on SOC stocks in organic farming systems in temperate Europe. They found slight increase in top 10-15 cm, slight decrease in intermediate dept (down to 50 cm), followed by a slight increase again in 70-100 cm depth. The investigation reported in Gaudaré et al. (2023) indicates, though, that unless appropriate farming practices are implemented, expanding organic farming might reduce the potential for soil carbon sequestration. According to Lorenz et al. (2019), the demand for organic products will continue to grow driven by food safety concerns. Due to lower yields, however, natural ecosystems may be increasingly converted to agroecosystems to meet the demand with uncertain consequences for the environment.

Regenerative agriculture (RA) may be defined as “an approach to farming that uses soil conservation as the entry point to regenerate and contribute to multiple provisioning, regulating and supporting services, with the objective that this will enhance not only the environmental, but also the social and economic dimensions of sustainable food production” (Schreefel et al. 2020). As such, it consists of a range of different practices that vary between regions, farmers and farming systems. It often includes focus on reduced tillage, crop retention, cover crops crop residue management. These practices in combination have shown to increase SOC (Chahal and Singh 2020, Rhodes 2017). Regenerative agricultural practices do not only enhance carbon storage but reports also indicate improved soil fertility and crop yields in many situations (Rhodes 2017). In general, it seems likely that regenerative practices, particularly reduced or no-tillage and cover crops, have the potential to increase SOC content (Breil et al. 2021). Regenerative agricultural practices are not only likely to enhance carbon storage (Breil et al. 2021) but reports also indicate improved general soil fertility and crop yields in many situations (Rhodes 2017).

Conservation agriculture (CA) is based on many of the abovementioned principles and focuses on minimal soil disturbance, permanent soil cover, and crop rotation. The effects of CA on SOC stocks are not consistent and depend on various factors, such as soil type, climate, crop type, residue management, and duration of conservation agriculture. A global meta study showed that CA systems including legume residue retention in combination with manure and mineral N-admixing have considerable potential to increase SOC and total N in topsoil layers (Bohoussou et al. 2022). But, as with all the practices considered, research is required to identify opportunities, barriers, and trade- offs with other agronomic environmental goals in a range of environments.

Results of the impacts of agroforestry on soil C stocks from the boreal zone are scarce, but some studies show that agroforestry and intercropping can significantly impact soil organic carbon stocks in Europe. Heimsch et al. (2023). Trees increased C accumulation of the ecosystem, and thus, the net emissions were estimated to be smaller than without the tree row, but soil SOC stocks were not measured. Mayer et al. (2020) conducted a meta study on temperate climate zones worldwide and found that agroforestry systems sequester significant amounts of SOC in topsoil and subsoils. Zuazo et al. (2014) reported that forest, shrubland, and grassland in a Mediterranean agroforestry landscape had higher soil organic carbon stocks compared to abandoned farmland. Further, Kay et al. (2019) furhter emphasized the potential of agroforestry in sequestering carbon and mitigating environmental pressures in European farmland. It has generally been reported positive effects of diversified arable cropping systems on SOC content in European agroecosystems have generally been reported (Francaviglia et al. 2019).

DOI: 10.5281/zenodo.17430539

Forest management must incorporate adaptive strategies to address climate change impacts, such as altering tree species composition, adjusting rotation periods, and modifying stand structures to maintain forest productivity and resilience (Jandl et al. 2019). Maintaining genetic diversity and resilience of forest ecosystems is crucial. This includes selecting tree species and genotypes that are better adapted to future climatic conditions, such as increased drought risks (Keenan 2015).

Effective climate change adaptation in marginal and alpine systems requires managing the impacts of shifting conditions on these fragile ecosystems. Adaptation strategies are essential for preserving biodiversity, ecosystem functions, and agricultural productivity. In alpine grasslands, climate change may alter plant species composition, potentially stabilizing primary production despite warming. However, these changes often lead to 8deeper root systems, which can influence soil carbon storage dynamics (Liu et al. 2018). Marginal populations of plants, such as those in alpine environments, may exhibit strong local adaptations to environmental stressors like frost. These adaptations are crucial for survival but may be limited by genetic diversity (Kreyling et al. 2014).

The investigation has identified following bottleneck:

Complexity and unclear mechanisms of SOC dynamics hinder understanding and application in climate adaptation strategies.

Suggested actions include:

- *(i) More experimental research is needed to study the long-term dynamics of trade-offs and synergies in SOC sequestration under various soil management strategies;*
- *(ii) There is also need to developing models and monitoring programs to better understand soil carbon stocks and degradation is crucial;*
- *(iii) Research should provide further knowledge on how soil structure, management practices and extreme weather events impact organic carbon stocks, and how this interacts with functional biodiversity. To assess these effects, research on harmonizing measuring, accounting, monitoring and model development across Europe is required It's also*
- *(iv) It's also essential to provide regional-specific long-term knowledge for tailoring adaptation strategies;*
- *(v) There is also a need to increase the understanding on the indirect effects of adaptation practices on soil functions and biodiversity.*
- *(vi) Research should focus on practices that promote SOC accumulation while balancing trade-offs between climate adaptation, food security, and ecosystem services;*
- *(vii) Transfer of existing research to practical applications remains insufficient (iii) assess these effects, research on harmonising measuring, accounting, monitoring and model development across Europe is required*

Knowledge gap 2: Biodiversity - interaction between soil carbon and soil biology

The investigation has identified the following knowledge development gap:

There is limited understanding of how soil biodiversity influences carbon cycling processes and the lack of comprehensive data on soil biodiversity across different regions and scales. While there is growing evidence linking plant diversity to soil carbon cycling, there is limited information on how soil biodiversity itself influences these processes.

The „Convention on Biological Diversity (CBD)“ (www.cbd.int) defines soil biodiversity as "the variation in soil life, from genes to communities, and the ecological complexes of which they are part, that is from soil micro-habitats to landscapes." It encompasses the variety of life below ground, including microorganisms, microfauna, mesofauna, and macro/megafauna. Soil biodiversity blends encompasses four complementary dimensions of soil systems: soil physics, soil chemistry, soil biology, and soil ecosystem functions. It relates to specific ecological indicators and includes a wide variety of soil- related Essential Biodiversity Variables (EBVs) to track the state and dynamics of global soil biodiversity and ecosystem functioning over time (Guerra et al. 2021).

DOI: 10.5281/zenodo.17430539

Soil biodiversity plays a critical roles in delivering ecosystem goods and services, such as nutrient cycling, water regulation, and soil structure maintenance. Biodiverse ecosystems may enhance SOC storage capacity and research can identify which plant species or microbial communities promote SOC accumulation (Chen et al. 2020, Chen et al. 2018). Plant communities enhance SOC through root exudates, litter quality and mycorrhizal associations, and investigating these feedback loops may help designing effective climate adaptation strategies. Moreover, biodiversity does affect SOC response to land use changes, and the relationships vary across ecosystems, climates, and soil types. There is an intricate relationship between SOC, soil biodiversity and ecosystem resilience in global soils.

High soil biodiversity supports various soil ecosystem functions and increases the system's ability to withstand and recover from environmental changes (Delgado- Baquerizo et al. 2025), and diverse plant species and soil organisms improve nutrient cycling and soil fertility (Furey and Tilman 2021). This is achieved through interactions among soil organisms, which enhance nutrient availability and storage, leading to increased soil fertility and reduced fertilizer needs (Delgado-Baquerizo et al. 2020). There is evidence that that high soil biodiversity increases ecosystem stability, resistance to environmental changes, and protection against diseases (Wang et al. 2025). These functions collectively contribute to a more robust and sustainable soil ecosystem, capable of adapting to and recovering from various environmental challenges (Bender et al. 2016, Brussaard et al. 2007), and soil health, high biodiversity and conservation of soil organic carbon are strongly connected (Chen et al. 2020, Lal 2016). It is important to note, however, that in some terrestrial ecosystems, the functional biodiversity is naturally low, particularly in marginal and extreme environments. This low biodiversity is characteristic for such systems, but this results in limited functional redundancy, making these ecosystems particularly susceptible to disturbances (Wall and Virginia 1999).

High plant biodiversity boosts plant productivity and root biomass, enhancing microbial growth and activity (Prommer et al. 2020). This leads to greater carbon inputs into the soil and improved carbon sequestration. Maintaining high levels of plant and soil organism diversity is essential for improving soil carbon storage and mitigating climate change impacts. Land-use practices that promote biodiversity, such as organic farming and diverse plantings, are beneficial for SOC conservation (Maron et al. 2018). However, the complexity of mechanisms at play is not yet well understood. For example, mixed species stands with low diversity in root architecture have recently been found to contribute to soil C storage more than those displaying contrasting root-system architecture (Yin et al. 2025). These insights underscore the importance of integrating biodiversity considerations into land management and policy decisions to enhance soil carbon sequestration.

Experimental evidence drawn from biodiversity ecosystem functioning experiments has generally shown that higher plant biodiversity leads to both higher aboveground and belowground plant productivity and concordantly higher soil carbon. In 1994, Tilman and Downing reported that preservation of biodiversity is essential for the maintenance of stable productivity in ecosystems (Tilman and Downing 1994). It may be the case that in a grassland clay rich soils, where essential nutrients are limiting, that the best yielding monoculture species may be superior to a mixture of plant species for producing biomass and storing soil carbon. However, there are also a host of what ecologists call „niche differences" that could explain why in some cases a higher number of species would yield greater soil carbon. For example, CAM can plant species can differentiate in hot and dry vs cold and wet seasons, exhibiting different rooting depths, producing different types of litter that are differentially processed by the microbial community (Furey and Tilman 2021, Kraychenko et al. 2019, Lange et al. 2015, Lange et al. 2021, Perry et al. 2023, Spohn et al. 2023, Yang et al. 2019). Higher plant diversity can enhance soil multifunctionality and increase SOC stocks by promoting below-ground organism diversity, which in turn supports carbon sequestration (Schittko et al. 2022, Steinbeiss et al. 2008, Yin et al. 2025). The study by Steinbeiss et al. (2008), showed that higher species

DOI: 10.5281/zenodo.17430539

richness significantly increased carbon storage and reduced carbon losses across all soil depths. Species diversity was found to be more important than biomass production for soil carbon changes. Finally, they report that tall herbs seem to aid in reducing carbon losses below 20 cm depth early on. An important observation is that this effect may be consistent across different land-use types, including forests, grasslands, and croplands (Chen et al. 2020). In contrast, intensifying land use leads to a reduction in the number of soil biota functional groups, with fewer species that are more closely related taxonomically (Tsiafouli et al. 2015).

Biodiversity, both above- and below ground, is integral to maintaining and enhancing SOC in Europe. Diverse plant species and soil organisms contribute to carbon sequestration and overall ecosystem functionality. Land use changes and agricultural practices significantly influence these dynamics, with more diverse systems generally supporting higher SOC levels. Conservation efforts should focus on maintaining biodiversity to ensure the sustainability of soil carbon stocks. Li and colleagues (Li et al. 2024) examined croplands with varying SOC levels to explore the relationship between SOC decomposition and the diversity, composition, and networks of belowground communities, including archaea, bacteria, fungi, protists, and invertebrates. They reported that SOC is crucial for the structure and metabolic activities of belowground biota. Thus understanding the evolution of belowground communities and their feedback on SOC dynamics seems important for carbon cycling, biodiversity conservation, and carbon management.

Biodiversity in urban ecosystems remains a largely unexplored field. However, even in these environments, biodiversity appears to enhance ecosystem functions and services, particularly through soil carbon sequestration. Schittko et al. (2022) conducted a study in Berlin, Germany, and they found that plant diversity positively influences soil multifunctionality and organic carbon stocks by increasing the diversity of below-ground organisms. These benefits are seen in both native and non-native plant species, though they are more pronounced in native species. Therefore, increasing the diversity of plants and soil fauna in urban grasslands can improve soil multifunctionality and help mitigate climate change.

A study from South Africa addressed that although no clear global relationship exists, positive local and regional relationships highlight the potential value of biodiversity in enhancing carbon management, but that knowledge gaps still hinder effective policy development for co-managing biodiversity and carbon (Midgley et al. 2010). This is also acknowledged in the study by Chenu et al. (2019), reporting that while existing knowledge and tools address many questions, further research is needed, especially on practices and the role of soil microorganisms in stabilizing soil organic matter. Protecting natural areas helps safeguard biota and reduce atmospheric carbon emissions, and including the interaction between soil biodiversity and soil carbon content, could increase funding opportunities for conservation (Sheil et al. 2016).

Evidence points to the need for further research to understand the role of biodiversity in SOC dynamics, the impact of land use management practices, and how to integrate soil biodiversity into policy and conservation efforts. Additionally, it is crucial to investigate how climate change and environmental conditions interact with biodiversity and to better understand belowground biological processes.

The investigation has identified the following bottlenecks:

(i) The lack of understanding of the mechanisms driving the observed congruence between biodiversity and carbon stocks limits the ability to predict and manage ecosystem services effectively.

(ii) Limited knowledge about how belowground communities—particularly microbes and invertebrates—regulate SOC turnover and ecosystem functioning constrains the development of holistic soil management strategies.

(iii) The unclear influence of biodiversity on SOC dynamics in novel ecosystems, such as those with high non-native species presence or urban disturbances, hampers the formulation of adaptive conservation and restoration practices.

(iv) The poorly understood interplay between plant litter inputs and microbial respiration

DOI: 10.5281/zenodo.17430539

across ecosystems creates a bottleneck in determining how plant diversity influences SOC accumulation and stability.

(v) The lack of clarity on how different biodiversity measures—such as species richness and functional traits—affect carbon stocks, especially in forest ecosystems, impedes the integration of biodiversity into carbon management frameworks.

(vi) Current policy frameworks are not fully equipped to address the intricate and dynamic interactions between biodiversity and SOC, creating a bottleneck in implementing effective climate and conservation strategies.

(vii) The lack of integration of recent scientific insights—particularly regarding the role of soil microorganisms and biodiversity in stabilizing soil organic matter—into agricultural and forest management practices hinders efforts to enhance SOC storage at scale.

(viii) Uncertainty about how soils should be used for carbon storage hinders climate mitigation planning.

(ix) Limited research and political sensitivity around carbon sequestration techniques hinder policy support and long-term adoption.

Suggested actions include:

(i) Integrate belowground biological processes into SOC models to improve carbon management strategies.

(ii) Developing high-resolution maps and models to predict soil biodiversity and SOC is crucial. This includes using digital soil mapping and regression analysis to link soil attributes with biodiversity.

(iii) An integrative approach that includes setting baselines, monitoring threats, and establishing soil indicators is recommended.

(iv) Encouraging sustainable land-use practices and reducing agricultural intensification can help preserve soil biodiversity. Providing incentives for sustainable practices and improving knowledge access are also suggested.

(v) Providing incentives for sustainable practices and improving knowledge access are also suggested.

(vi) Strengthen the role of knowledge brokers and improve the relevance of research activities for land users through targeted advice and information dissemination.

(vii) Encourage research that integrates social and ecological systems to develop comprehensive soil carbon management strategies.

Knowledge gap 3: Policy making and decision support

The investigation has identified the following knowledge application gap:

The gap between existing scientific knowledge and its practical implementation in policy and land management creates a bottleneck in efforts to conserve and enhance SOC stocks. Without effective knowledge exchange and decision support, proven strategies remain underutilized, slowing progress in SOC restoration and climate resilience.

European soil carbon management is supported by various policy frameworks and social strategies, including the European Green Deal, Common Agricultural Policy (CAP), and carbon credit systems. The European Green Deal aims to make the EU climate-neutral by 2050, incorporating soil protection measures such as reducing chemical pesticide use and increasing organic farming. The European Climate Law also addresses SOC enhancement and wetland maintenance (Montanarella and Panagos 2021). The CAP supports soil carbon management through incentives for sustainable practices and the integration of soil carbon sequestration into climate-smart agriculture. However, current policies are deemed insufficient for large-scale adoption, suggesting a need for more focused regulatory frameworks (Verschuuren 2018). Carbon farming practices incentivized through carbon credit systems reward increased soil carbon stocks (Criscuoli et al. 2024). The credit system risks masking harmful practices, especially outside the EU, through offsetting, while also creating dependency on external, non- productive funding, echoing inefficiencies seen in parts of the CAP. Recommendations include expanding eligible practices and setting regulatory baselines to ensure effective implementation. The EU Soil Observatory collects data and develops indicators

DOI: 10.5281/zenodo.17430539

to assess progress towards soil management targets, supporting policy development and implementation (Montanarella and Panagos 2021).

Despite these initiatives, challenges persist in policy adequacy and knowledge dissemination. To ensure effective soil carbon management and climate change mitigation, it is essential to address these issues through targeted interventions and local adaptation strategies. Increasing SOC stocks is crucial for enhancing soil fertility, food security, and climate change mitigation, but significant knowledge and application gaps remain in policymaking and decision support.

There is a need to clearly differentiate between SOC storage and sequestration and to develop methods for accurately estimating potential SOC gains from various agricultural practices. Chenu et al. (2019) elaborate on how implementing management strategies to boost SOC stocks addresses several key questions and considerations, including methods to increase SOC stocks, the rate and duration of these increases, prioritizing storage areas, estimating potential carbon gains, and selecting suitable agricultural practices. According to Maenhout et al. (2024), soil management strategies (SMS) can enhance SOC stocks, reduce greenhouse gas (GHG) emissions, and decrease nitrogen (N) leaching. However, some SMS may increase emissions of GHGs like nitrous oxide (N_2O) or methane (CH_4), offsetting the benefits of SOC sequestration. Understanding these trade-offs and synergies is essential for selecting sustainable SMS for European agriculture, but knowledge remains limited.

The effect of policymaking and support on the long-term dynamics of SOC stocks under different management practices and climatic conditions is also underexplored (Maenhout et al. 2024, Wang et al. 2022). Globally, much research predominantly focuses on ecological aspects, with a lack of integration of social components, such as farmer perspectives, which are essential for the sustainability of carbon-building practices (Amin et al. 2020). The study by Thorsøe et al. (2023) highlights that stakeholders emphasize the need for better knowledge transfer to practitioners and recommend raising awareness, improving research relevance, and providing incentives. Moreover, tailoring soil management techniques to local conditions, such as climate and farming systems seems essential to enhance SOC (Mäkipää et al. 2024). Common barriers seem to include biophysical conditions, financial support, and advisory service quality. Opportunities lie in economic incentives, regulatory harmonization, and fostering long- term planning and resilience (Mills et al. 2020).

The investigation has identified the following bottlenecks:

(i) Uncertainty about how soils should be used for carbon storage hinders climate mitigation planning.
(ii) Limited research and political sensitivity around carbon sequestration techniques hinder policy support and long-term adoption.

Suggested actions include:

(i) Strengthen the role of knowledge brokers and improve the relevance of research activities for land users through targeted advice and information dissemination.
(ii) Encourage research that integrates social and ecological systems to develop comprehensive soil carbon management strategies.
(iii) Promote studies in underrepresented regions to ensure a more global understanding of SOC dynamics.
(iv) Invest in monitoring and modelling frameworks to provide robust data for decision-making and policy development.

3.2 Prioritized knowledge gaps

Knowledge gap 4: Soil carbon monitoring, reporting and verification (MRV)

The investigation has identified following knowledge development gap:

There is a significant lack of understanding and infrastructure for monitoring, reporting, and verifying SOC across Europe.

DOI: 10.5281/zenodo.17430539

Limited data, inconsistent methods, and lack of localized models hinder accurate monitoring and verification of SOC across Europe. This includes insufficient long-term datasets, non-standardized sampling methods, and a shortage of localized models that reflect environmental variables like climate, soil pH, and land cover, limiting the accuracy and effectiveness of SOC assessments for policy and land management. To effectively address content and quality of SOC stock, several methods exist ranging from laboratory measurements to remote sensing modelling. In short, the determination of SOC stocks requires measurements of bulk density, gravel content and SOC concentration in different depths. Careful, repeated field sampling followed by laboratory analysis following standardized and procedural guidelines are, however, necessary for accurate reporting and verification. Traditional analysis methods are often time consuming, so more recent methods, such as Visible–Near-Infrared (vis–NIR) Spectroscopy for SOC determination and Active Gamma-Ray Attenuation for bulk density can be relevant for some studies. However, gravel content may still require (wet) sieving (England and Viscarra Rossel 2018). For remote sensing eddy covariance is a costy application useful for measuring respiration and carbon fluxes, providing insights into regional SOC sequestration when used in combination with simulation modelling (Zeng et al. 2020). There is a challenge in developing cost effective methods for detecting changes in SOC resulting from changes in management etc., but several direct field applicable methodologies exist, such as laser-induced breakdown spectroscopy (LIBS) (Cremers et al. 2001), inelastic neutron scattering (Wielopolski et al. 2000), Mid-Infrared and Near-Infrared Diffuse Reflectance Spectroscopy (McCarty et al. 2002).

Existing soil monitoring networks in Europe are inadequate for comprehensive SOC accounting. They often lack biological and physical parameters, focusing predominantly on chemical attributes, which limits their ability to assess soil functions comprehensively (van Leeuwen et al. 2017). There is a lack of standardized methods and comprehensive datasets, particularly for agricultural soils. This results in inconsistent data across different regions and countries, (Rodrigues et al. 2021), making it difficult to compare and integrate findings at a European scale (Lugato et al. 2014). Efforts to model SOC stocks are ongoing, but these models often require improvements to account for regional environmental factors and land-use changes accurately (Rial et al. 2017). The impact of environmental factors such as climate, soil pH, and land cover on SOC storage is not fully understood, necessitating more localized and specific models (Prechtel et al. 2009, Rial et al. 2017).

The investigation has identified following bottlenecks:

(i) Lack of long-term datasets, standardized sampling protocols, and harmonized data across regions, prevents accurate, comparable SOC assessments across Europe, limiting the reliability of MRV systems.

(ii) Traditional SOC measurement methods are time-consuming, and newer technologies (e.g., vis–NIR, LIBS, neutron scattering) are underutilized or costly and this slows down large-scale, cost-effective SOC monitoring and reduces the feasibility of frequent updates.

(iii) SOC models often fail to account for key environmental variables like climate, soil pH, and land cover, reducing the accuracy of SOC predictions and limits the ability to tailor management strategies to local conditions.

(iv) Existing monitoring networks focus mainly on chemical properties and lack biological and physical indicators, limiting comprehensive understanding of soil functions and their role in SOC dynamics, weakening the foundation for effective MRV and land-use policy.

Suggested actions include:

(i) Develop unified protocols and long-term monitoring programs across Europe.

(ii) Create open-access databases to integrate data across regions and land uses.

(iii) Support the development and field use of rapid SOC assessment tools.

DOI: 10.5281/zenodo.17430539

(iv) Provide technical training for researchers and land managers in modern SOC methods.
(v) Refine models to include climate, soil pH, and land cover for better regional accuracy.
(vi) Integrate biological and physical indicators into existing networks for holistic SOC assessment.

Knowledge gap 5: SOC in circular bioeconomy, LCA

The investigation has identified following knowledge development gap:

The effects of organic residues on soil carbon processes and ecosystem services are not fully understood, while potential risks from pollutants, microplastics, and unregulated toxic compounds raise concerns about soil health and safety.

In a sustainable bioeconomy, recycling of nutrients from organic residues is imperative (Hellsmark et al. 2016, Sawatdeenarunat et al. 2016). The circular economy emphasizes maximizing resource reuse and minimizing waste, which directly influences soil management. Efficient soil and land management are essential for the circular economy to function effectively, as soils play a critical role in food production, water filtration, and carbon storage (Breure et al. 2018). There is a huge diversity in organic residues depending on their origin and the type of process involved in their production. Hence, it is essential to distinguish between organic wastes, residues, and processed products like compost and digestate. Certified compost and digestate, produced through regulated biological processes, are no longer considered waste but valuable soil amendments under EU law, provided they meet strict quality and safety standards (Regulation (EU) 2019/1009 2019). Application of organic residues as soil amendment and fertilizer to agricultural land gives the opportunity of recovering the nutrients, primarily N and P, and of potentially improving soil quality by adding organic matter. The European Union's new Soil Strategy for 2030 aligns with the circular economy by setting a framework for protecting and restoring soils, however, only materials that comply with legal thresholds can and should be used in agriculture; those exceeding limits remain classified as waste. Harmonized quality standards and proper life cycle assessments are crucial to ensure their safe and effective use. This strategy also covers sustainable waste management (Panagiotakis and Dermatas 2022). The circular economy principles are integrated into broader environmental strategies, such as the European Green Deal. The European Union promotes the use of organic inputs on arable land to maintain or increase SOM, particularly in carbon-depleted soils. This is part of broader strategies to offset greenhouse gas emissions and ensure soil protection across member states (Marmo 2008).

Long-term application of organic amendments, such as compost and sludge, can significantly increase SOC contents. Studies also show that the repeated application of organic residues enhances soil biological functions, including microbial biomass carbon and enzymatic activity, which are crucial for maintaining healthy soil ecosystems (e.g. Diacono and Montemurro 2010). Regular addition of composted organic residues, for instance, improves soil physical properties, such as aggregate stability and bulk density, and enhances soil fertility, increased crop yields and improved crop quality without reducing yield quality (Agegnehu et al. 2016).

However, organic residues may also increase greenhouse gas production through the input of microbial substrates and increased mineralization of N. Pyrolyzing residual biomass for biochar application to soil is the main method for C sequestration in soils, that also has clear positive effects on reducing N_2O emissions form soils (Guenet et al. 2021). The soil plays a key role in a circular economy and sustainable society, but there is significant lack of knowledge concerning safe and energy-efficient recycling of organic residues in soil, and its impact on SOC stocks and soil health.

Policies often prioritize meeting crop N and P demands. Strict environmental regulations govern the use of organic residues in agriculture, with a particular focus on the treatment of animal manure and the management of farm nutrient balances. These regulations are designed to prevent environmental contamination and promote sustainable waste management practices (Lourenzi et al. 2021, Westerman and Bicudo

DOI: 10.5281/zenodo.17430539

2005). Mixed municipal solid waste compost, is no longer going to be representative for compost and digestate practices in the EU due to the obligation to separately collect bio-waste. However, persistent contaminants such as PFAS, and biochar containing heavy metals (Sørmo et al. 2024) can still be introduced, highlighting the need for careful monitoring, regulation, and ongoing research to safeguard soil health and food safety. Finally, composts and sewage sludge may contain significat amounts of microplastic fragments, depending on the origin of the material (Boctor et al. 2025). Hence, the use of organic residues for nutrient recycling and C addition is challenging, as we should not make use of organic residues if they transfer contaminants, pathogenic organisms, and unwanted plant species such as weeds to healthy soils. While circular economy principles emphasize resource efficiency, their direct influence on SOC stocks remains an area of study.

It would therefore be important that organic amendments, such as compost and digestate, intended for agricultural use, are consistently produced through improved and traceable waste management practices, ensuring compliance with the criteria set out in the EU Fertilizing Products Regulation (Regulation (EU) 2019/1009 2019). At the same time, it would be advisable to further harmonize at the European level the minimum quality requirements for compost and digestate to facilitate their safe use in agriculture and to ensure a level playing field across Member States. In order to correctly assess the intrinsic value of organic amendments such as compost and digestate, as well as their long-term effects, it is necessary to carry out a proper evaluation of the various ecosystem services provided by soil. Similarly, to perform a life cycle assessment (LCA) of organic amendments, the benefits of these products must be correctly estimated and evaluated. This is particularly true as not all LCA methodologies include emissions from reference scenario in which no composting takes place.

The investigation has identified following bottlenecks:

(i) Limited understanding of SOC and ecosystem impacts, limits accurate prediction of carbon sequestration potential and informed decision-making on residue use in sustainable land management.
(ii) Risk of soil contamination from organic residues limits safe application of organic residues and public trust in recycling practices within the circular economy.
(iii) Lack of harmonized quality standards and traceability limits safe, widespread adoption of organic amendments and a level playing field for sustainable agriculture.
(iv) Incomplete life cycle assessments (ICA) limits accurate environmental impact assessments and policy development for circular bioeconomy strategies.
(v) Regulatory prioritize nitrogen and phosphorus management, often overlooking broader soil health indicators and contaminant risks, hinders comprehensive soil protection and the integration of organic residue use into long-term soil carbon strategies.

Suggested actions include:

(i) Enhance research on microbial interactions and nutrient cycling in soils with organic amendments to improve carbon sequestration models and nutrient management strategies
(ii) Conduct more detailed studies on the effects of organic waste on various soil organisms to better understand and mitigate potential toxic impacts
(iii) Develop more precise and comprehensive methods for monitoring soil structure changes and pollutant levels, including advanced imaging and chemical analysis techniques.
(iv) Implement better waste management practices that consider the complex interactions of different waste types and their potential environmental impacts
(v) Increase data collection on soil physical, chemical and biological properties and promote sharing of findings to build a more comprehensive understanding of the effects of organic residue applications
(vi) Revising policies to account for the complex interactions of organic waste components and their long-term effects on soil health and ecosystem stability is crucial.

DOI: 10.5281/zenodo.17430539

Knowledge gap 6: SOC and Agronomic system approach

The investigation has identified following knowledge development gaps

There are several knowledge gaps on various aspects of agronomic practices for managing soil organic carbon stocks in agricultural soils, and long-term field experiments trying to elucidate the effect of different soil management practices on soil carbon stocks need long-term perspectives (and appropriate financing possibilities).

Sustainable food production requires increasing the productivity and efficiency of land, water, and other inputs while reducing the environmental impact and greenhouse gas emissions of agriculture. Adopting regenarative agricultural practices, such as reduced tillage, crop rotation, cover crops, and intercropping, can enhance SOC storage and restore soil quality, thereby strengthening long-term food security. However, the production benefits may not be apparent in the short or medium term.

Growing cover crops where soil would otherwise be bare has many benefits, including decreased NO^{-} leaching over winter and reduced soil erosion. However, their role in increasing SOC may have limitations in many European situations. Where cover crops can be grown, they may lead to some increase in SOC, though the magnitude may be less than often assumed. For example, a recent review calls into question the often- quoted view that cover crops can increase SOC by about 0.3 tC/ha/yr; see Chaplot and Smith (2023). Additionally, cover crops may contribute to increased nitrous oxide emissions due to the accumulation of organic nitrogen in the increased stock of soil organic matter (Guenet et al. 2021, Lugato et al. 2018).

The effects of tillage practices on SOC at different soil depths are not uniform and depend on various factors, such as soil type, climate, crop type, tillage practices (e.g. no tillage to high intensity, (Haddaway et al. 2017), tillage frequency and bulk density (Fornara and Higgins 2022). For example, a review of 351 studies from warm temperate and snow climate zones, found that SOC was significantly higher in no tillage soils compared to high intensity systems in the upper 30 cm soil layers, but no effect was found in the full soil profile. The higher SOC in the top layer in no tillage systems, however, may provide resilience to extreme weather conditions though (Haddaway et al. 2017). A recent study from a mediterranean climate, showed among other findings, that tilled wheat had greatest soil C stabilization at intermediate depts (30-60 cm), whereas no-tilled wheat had highest carbon stabilization and microbial biomass in the top-soil (0-30 cm) (Taylor et al. 2024). The increased SOC stabilization in topsoil was connected to better plant growth at no-tillage in Mediterranean (rather dry) climates. A study by Fornara and Higgins (2022) of 500 grassland fields in Northern Ireland, UK, showed that C and N stocks (mg/ ha) in the top 30 cm were not affected by frequency of tillage + reseeding, as differences in bulk density levels out the stock variation. Additionally, the risk of dissolved reactive phosphorus losses increases in no-till fields. The overall impact on water quality depends on the extent to which particulate phosphorus losses are reduced, and the proportion of that particle-bound phosphorus that becomes bioavailable once it enters surface waters (Daryanto et al. 2017, Iho et al. 2023).

Crop rotation is an important aspect of farming systems, but according to Land et al. (2017) there are not many comprehensive studies designed to unravel the effect of crop rotation on SOC stocks. Calculations indicate that perennial forages can increase below- ground SOC more than the common crops, especially if crop residues are not returned, or if the perennial forages are discontinued (Bolinder et al. 2012, Bolinder et al. 2007, Land et al. 2017). Perennial crop seems to increase the C storage and flux, more strongly in shallow soil (0-15 cm) compared to deeper soil layers (15-30 cm) (Means et al. 2022) in comparison to annual monoculture crop.

The investigation has identified following bottlenecks:

(i) Insufficient knowledge of how different soil management strategies affect SOC seques-

DOI: 10.5281/zenodo.17430539

tration, greenhouse gas emissions, and nutrient leaching, hinders development of integrated practices that balance productivity with environmental sustainability.

(ii) Lack of comprehensive and harmonized data on soil carbon stocks, degradation, and fertility across regions, hinders accurate assessment of soil conditions and targeted improvement strategies.

(iii) Limited empirical evidence on how specific agronomic practices influence SOC levels over time, limits effective evidence-based recommendations for sustainable farming systems.

(iv) Weak communication channels and limited collaboration between researchers, policymakers, and land managers, limits adoption and scaling of effective soil carbon management practices.

(v) Absence of consistent methods for measuring and comparing SOC outcomes across studies and regions, hinders cross-comparison, policy alignment, and coordinated action at national and EU levels.

Suggested actions include:

(i) More experimental research is needed to study the impact of pedoclimatic conditions and long-term dynamics of SMS on SOC and emissions

(ii) Developing models and monitoring programs to better understand soil processes is crucial

(iii) Increase awareness among stakeholders about the importance of SOC and sustainable soil management practices

(iv) Enhance the role of intermediaries who can effectively communicate research findings to practitioners and policymakers

(v) Align research activities with the needs of land users and ensure that findings are accessible and applicable

(vi) Introduce financial incentives, such as subsidies and payments for ecosystem services, to encourage the adoption of sustainable practices, and probably very important

(vii) Encourage direct communication among farmers and stakeholders to share experiences and best practices.

Knowledge gap 7: Urbanisation and SOC

The investigation has identified following knowledge development gaps:

There is limited data on SOC storage in urban areas, with high variability across land uses and regions. The effects of different urbanization pathways on SOC are poorly understood, and accurate SOC stock estimations and integrations into regional and national carbon budgets remain challenging.

Urbanization is the process of transforming rural areas into urban areas, which can have various effects on food production and SOC stocks. Urbanization significantly alters land use patterns, leading to changes in soil properties, and SOC stocks vary widely across different urban environments (e.g., parks, sealed surfaces, green spaces). Furthermore, urban soils face unique challenges due to compaction, pollution, and limited space. Urban systems involve material flows (e.g., waste, organic matter) that impact SOC dynamics. Thus, integrating soil health and carbon sequestration goals into urban planning and policies will be challenging. In view of the need for housing increased populations in many European countries, some loss of agricultural land due to urbanization seems inevitable. Generally, there is a major conflict of interest between urbanization and the protection of productive soil. High quality soil for agriculture is a non-renewable resource since it takes centuries to build up few centimetres of productive soil. The conversion of agricultural land to urban land is de facto an irreversible process (Amundson et al. 2015), as new use may decrease the land's ability and capacity to supply food and other vital ecosystem services (Tan et al. 2009). Historically, urbanization has occurred close to our most productive farmland (Ferrara et al. 2014), and most remaining farmland is located close to urban settlements. Thus, urban sprawl is consuming fertile agricultural land for urban use worldwide (Skog and Steinnes 2016). How to combine increased food production and soil organic matter conservation with increased urbanization and high pressure on productive ag-

DOI: 10.5281/zenodo.17430539

ricultural land, i.e., multifunctional land use, is a challenge. The EU commission has onset several strategies, such as the biodiversity long-term plan to protect nature and reverse the degradation of ecosystems. The strategy aims to put Europe's biodiversity on a path to recovery by 2030 (Eu comission 2020), to protect and restore soils, and ensure that they are used sustainably and finally the „science for Environment Policy: No net land take „ future brief, to outline what measures can avoid, reduce or compensate for land take (EU comission 2016).

The investigation has identified following bottlenecks:

(i) SOC stocks vary widely across urban land uses, and the effects of urbanization pathways on SOC, are poorly understood. This limits accurate assessment and integration of urban SOC into carbon budgets and climate strategies.
(ii) Urbanization often targets fertile agricultural land, leading to irreversible soil loss and reduced capacity for food production and carbon storage. This undermines long-term food security, ecosystem service provision, and sustainable land use planning.
(iii) Soil health and carbon sequestration goals are not systematically incorporated into urban development policies. This restricts multifunctional land use strategies that balance housing, food production, and environmental sustainability.
(iv) Urban soils face unique challenges such as compaction, pollution, and limited space, which affect their ability to store carbon and support ecosystem functions. This limits effective use of urban green spaces for climate mitigation and biodiversity enhancement.

Suggested actions include:

(i) Implement soil and land-use management practices that enhance SOC stocks and support ecosystem services in urban areas
(ii) Increase efforts to collect and analyse SOC data across various urban land uses and regions to improve accuracy in SOC stock estimations
(iii) Encourage the development of urban green spaces, such as parks and gardens, which have been shown to retain higher SOC stocks compared to other urban land uses
(iv) Adopt strategies to control urban sprawl and promote resource-efficient land use, which can help mitigate the negative impacts on SOC stocks

Knowledge gap 8: Education and awareness raising on SOC

The investigation has identified following knowledge application gap:

The main knowledge gap in Europe concerning the importance of SOC, particularly in education and awareness, lies in the effective communication and application of existing research to practitioners and the public. This disconnect limits the adoption of sustainable soil management practices essential for climate change mitigation and soil health.

Awareness of soil health's importance has grown in recent years. Initiatives like the PREPSOIL project contribute to the Soil Mission by enhancing knowledge and awareness of soil needs among stakeholders across Europe. Such projects address the critical need to educate diverse audiences on the role of soil organic carbon conservation in sustaining life and natural resources, from individuals to society as a whole. Despite its significance, soil remains widely under-communicated, including within educational institutions at all levels. This highlights the clear connection to the eighth mission objective on soil literacy, which emphasizes both general soil health and the importance of its carbon stocks.

Soil C storage refers to an increase of soil C stocks, while soil C sequestration implies a net removal of atmospheric CO_2. However, these terms are often used interchangeably or ambiguously, which can cause confusion and misunderstanding among different stakeholders and audiences. Recently, Janzen (2024) published

DOI: 10.5281/zenodo.17430539

an important adjustment in how we should appreciate SOC, which is easily under communicated in the discussion about conserving and increasing SOC: Rather than using the term ‘sequestration,’ we might instead speak of SOC ‘stewardship,’ which captures the full range of SOC rather than just a narrowly defined ‘stable’ or ‘persistent’ fraction. This shift in perspective could reshape research questions, for example, is long-term stability necessary for SOC to effectively store excess atmospheric CO_2? ‘Stewardship’ recognizes the continuous cycling of SOC, emphasizing the need to manage both stored carbon and the ongoing flows that sustain ecosystem functions.

Therefore, it is crucial to promote education and awareness not only about soil quality and health but also about the global benefits of effective SOC management, particularly in climate change adaptation and sustainable food security. There is a need to improve fellow citizens, land managers, politicians and policymakers common understanding of SOC dynamics and its central role. Communicating this has been challenging, partly due to the complexity of organic C composition and its dynamic behaviour in soil, as well as its connections to key soil functions such as structure, biodiversity, and elemental cycles (Chenu et al. 2019).

The knowledge gaps on communicating the role and importance of SOC to society and its role in providing and sustaining a number of the soil ecosystems, seems to be mostly related to communication and suitability of soil data management. There is a lack of comprehensive models and monitoring programs to address the loss of SOC in various systems, and its importance for water infiltration and reducing soil compaction for instance (Thorsøe et al. 2023). Moreover, there is a need to clearly differentiate between SOC storage and sequestration, as they have different implications for climate change adaptation and mitigation (Chenu et al. 2019, Janzen 2024), and stakeholders have varying perceptions of soil quality and functions, indicating a need for regionally relevant advice and credible information on sustainable management practices (Bampa et al. 2019).

The investigation has identified following bottlenecks:

(i) Existing SOC knowledge is not effectively communicated or applied by practitioners and the public. This limits the adoption of sustainable soil management practices and climate mitigation strategies.
(ii) SOC and soil health are underrepresented in education and public discourse. This weakens societal understanding of soil's role in climate adaptation, food security, and ecosystem services.
(iii) Terms like “SOC storage” and “sequestration” are often used interchangeably, leading to misunderstanding. This creates confusion in communication, policy development, and alignment of research and management goals.
(iv) Stakeholders have diverse perceptions of soil quality, and there is limited access to tailored, trustworthy information. This reduces the effectiveness decision-making and adoption of context-specific sustainable practices.
(v) There is a lack of comprehensive models and monitoring systems to track SOC loss and its impact on soil functions. This undermines evidence-based policy, long-term planning, and evaluation of soil management outcomes.

Suggested actions include:

(i) Enhancing the role of intermediaries who can translate scientific findings into practical advice for land users,
(ii) Encouraging communication among farmers and stakeholders to share best practices and experiences,
(iii) Providing tailored advice and information that considers local environmental and socio-economic conditions,
(iv) Raising awareness about the importance of SOC and strengthening educational programs are essential. This includes providing credible information and locally relevant advice to stakeholders,
(v) Funding for applied research, and support for training programs can encourage the adoption of sustainable practice.

DOI: 10.5281/zenodo.17430539

Knowledge gap 9: Forest management and SOC

The investigation has identified following knowledge development gap:

The main research gap in forest SOC management is understanding how different practices impact SOC stocks and interact with environmental factors like climate change. Addressing this requires site-specific studies, large dataset integration, and comprehensive management frameworks.

Forest soils store almost half of the total organic C in terrestrial ecosystems, and forest management practices can influence the rates of input or release of C from soils (Mayer et al. 2020, Mäkipää et al. 2023, Ontl et al. 2020). An important factor for soil C stocks, for Europe and globally, is to maintain existing forest cover and avoid its removal or degradation. Forest management can have various objectives, such as timber production, biodiversity conservation, recreation, C sequestration, and other ecosystem services. It is, however, likely that, in many forest situations, the main societal goal will be habitat for wildlife with managements being tailored for different species in different situations. Forest management require thus a holistic approach serving several ecosystem services other than simply exploring its potential in storing soil C. Consideration of C stocks will thus be a secondary factor. Many factors influence the interactions between forest management and SOC stocks, such as forest type, disturbance, soil type, climate, time (Ahmed et al. 2012, Jandl et al. 2021) and the carbon use efficiency (CUE; Qiao et al. 2019, Tao et al. 2023). Boosting SOC stocks addresses several key questions and considerations. Clear-cutting in Nordic and Canadian forests leads to a significant, decadal decline in forest floor SOC (Johannesson et al. 2025). This decline persists for many years after harvesting, highlighting a long-term impact of clear- cutting on forest soil carbon storage. The decline is most pronounced in the organic layer (forest floor), while the mineral soil shows little to no significant change in SOC stocks. The loss of SOC is attributed to increased decomposition rates and reduced litter input following the removal of trees. SOC in the forest floor may begin to recover several decades after clear-cutting, but full recovery to pre-harvest levels can take 30–50 years or more (Clarke et al. 2021).

Several studies underscore the need for sustainable management practices and innovative solutions to meet the growing demand for timber and forest waste as bioenergy in the context of climate change. The demand for wood-based energy is expected to increase, but the C impacts of forest bioenergy are uncertain (Giuntoli et al. 2020). Forest residues can also be used for biochar production, with substantial climate benefits even after all environmental costs associated with production and application are discounted through life cycle analysis (Tisserant et al. 2022). This is further complicated by the potential effects of climate change and air pollution on forest productivity and C sequestration (Matyssek et al. 2012). The removal of forest residues for bioenergy could also have negative consequences for how forest systems provide and sustain their ecosystem services (Clark 2012).

There is a need for advanced modelling techniques like boosted regression trees (BRT) and other machine learning models can improve SOC stock estimates by identifying key predictors such as groundwater level, clay fraction, and tree genus (Ottoy et al. 2017). In addition geostatistical models, using climate and land cover data, that can predict current and future SOC stocks, providing insights into how SOC might change under different climate scenarios (Yigini and Panagos 2016). And simulation models which are used to simulate SOC stocks and changes, offering a way to assess the impact of land use and climate change on SOC (Hernández et al. 2017). Complementary to this, future climate scenarios suggest varying impacts on SOC stocks, with potential increases or decreases depending on the region and forest type. Models should be developed to predict an overall increase in SOC stocks in Europe by 2050 under various climate scenarios (Yigini and Panagos 2016). Advancing SOC

DOI: 10.5281/zenodo.17430539

research and management through modelling, forest practice analysis, and climate adaptation can improve implementation, leading to better predictions and conservation strategies in European forests.

The investigation has identified following bottlenecks:

(i) Forest management often prioritizes biodiversity, timber, or recreation over soil carbon storage, and SOC is frequently treated as a secondary consideration. This limits the integration of SOC conservation into forest policy and practice, reducing the potential for forests to contribute to climate mitigation.
(ii) Practices like clear-cutting and residue removal for bioenergy can lead to long-term SOC losses, especially in the forest floor layer. This limits the long-term stability of forest soil carbon stocks and the sustainability of bioenergy strategies.
(iii) Despite the availability of advanced modelling tools (e.g., machine learning, geostatistics, simulation models), they are underutilized in forest SOC assessments. This limits accurate prediction of SOC changes under different management and climate scenarios, hindering informed decision-making and adaptive forest planning.

Suggested actions include:

(i) Utilize large observational databases and meta-analyses can help synthesize existing data and provide a clearer picture of SOC dynamics across different regions and management practices.
(ii) Creating comprehensive classifications and thesauri, like DATA4C+, can help standardize the description of management practices and improve the quality of meta- analyses, aiding in the identification of effective SOC management strategies.
(iii) Research should prioritize understanding how climate change scenarios affect SOC, as these changes pose significant risks to SOC stocks, particularly in temperate forests.

Knowledge gap 10: EU footprints of soil carbon outside Europe

The investigation has identified following knowledge development gap:

The main gap in understanding European impacts on global SOC stocks is the lack of comprehensive monitoring of how European consumption and land use affect SOC worldwide. This is compounded by insufficient data on environmental factors influencing SOC storage and the effects of trade and consumption patterns outside Europe.

The import of food and fiber into Europe has a complex and varied impact on SOC stocks in soils outside of Europe. Frank et al. (2015) found that changes in SOC stocks depend on management regime and environmental factors, with a potential for carbon sequestration in European cropland. However, if C sequestration as opposed to food production is prioritized in Europe, this would lead to increased imports of food. Much being likely to be grown on recently cleared land elsewhere in the world with the resulting loss of SOC, and increased CO emissions, in those regions. For instance, if organic farming increases, this may come at the expense of SOC loss at another site (Gaudaré et al. 2023). To improve our understanding of SOC stock outside Europe, standardized estimation methods, comprehensive data sets, and accurate mapping techniques is needed (Aksoy et al. 2016, Lorenz et al. 2019, Lugato et al. 2018, Wiesmeier et al. 2012).

There is a need for improved methodologies to monitor and identify environmental factors that control SOC storage, as current models often rely on geographically non-stationary processes that vary by location (Rial et al. 2017). And the role of European consumption in driving SOC changes outside Europe is not well understood, particularly how trade and consumption patterns contribute to SOC losses in other regions (Wilting et al. 2021). Addressing knowledge gaps on European impacts on global SOC stocks requires improved monitoring, policy integration, and data standardization to better understand SOC dynamics and reduce the effects of European consumption on global soil C.

DOI: 10.5281/zenodo.17430539

The investigation has identified following bottlenecks:

(i) Prioritizing carbon sequestration in Europe may lead to increased food and fiber imports from regions where land is cleared for agriculture, causing SOC loss and CO_2 emissions abroad. As a result, the global climate benefits of European SOC strategies may be undermined, shifting environmental burdens to other regions.
(ii) There is a shortage of standardized methods, comprehensive datasets, and accurate mapping techniques for assessing SOC stocks outside Europe. This gap hampers reliable global assessments of SOC dynamics and weakens the ability to track the external impacts of European consumption.
(iii) The role of European trade and consumption in driving SOC changes in other regions is not well understood. This lack of insight constrains informed policymaking and the integration of global SOC considerations into European sustainability and trade strategies.

The actions include:

(i) Enhance the integration of research findings into policymaking to address the impacts of European consumption on global SOC stocks. This includes considering trade impacts in national and regional policies
(ii) Promote standardization in SOC measurement and data sharing across countries to improve the accuracy of SOC assessments and facilitate better policy decisions
(iii) Implement incentives for sustainable soil management practices that enhance SOC sequestration, such as carbon credits and other financial mechanisms.

Summarisation of prioritized knowledge gaps

An overview table of the prioritized knowledge gaps, their sector impact, bottlenecks and suggested actions can be found under Suppl. material 1.

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DOI: 10.5281/zenodo.17430539

DOI: 10.5281/zenodo.17430539

Soils for Europe

Outlook on the knowledge gaps to reduce soil sealing and increase the reuse of urban soil

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Introduction

The third specific objective of the Soil Mission is to achieve "no net soil sealing and increase the reuse of urban soil" (*European Commission: Directorate-General for Research and Innovation 2022 p. 16*). Soil sealing is considered as the main process that causes land degradation in urban areas (European Environment Agency et al. 2022). When soil is sealed, an impermeable layer interrupts the connection between the soil and the atmosphere, leading to the loss of soil resources, biodiversity, and ecosystem services. The process of soil sealing is strictly linked to land take, i.e. the conversion of natural and semi-natural land into artificial land (see definitions in Table 1). The Soil Mission implementation plan estimates that the area with poor soil health due to soil sealing is probably <1% of EU land, but can be as high as 2.5%. These figures are based on the assumption that sealed areas represent around 50% of artificial areas, which cover 4.2% of the EU. Locally, sealed surfaces can reach very high levels, with some areas exhibiting rates as high as 70% (Decoville and Feltgen 2023). Both soil sealing and land take have been steadily growing during the last decades (European Environment Agency et al. 2022). Between 2000 and 2018, artificial areas expanded by 7.1%, with net land take averaging 440 km²/year between 2012 and 2018, primarily at the expense of arable lands, pastures, and grasslands. Concerning the second part of the objective, soil reuse refers to the use of excavated soil from construction sites for other purposes (Reicosky and Wilts 2005). In many European countries, excavated soils are still classified as waste, contributing over 520 million tonnes to the total waste generated in the EU in 2018 (Scialpi and Perrotti 2022).

The European Commission proposal for a Directive on Soil Monitoring and Resilience drafted in 2023 and currently under trilogue negotiations, aims to specify the conditions for healthy soils and to lay out regulations to promote sustainable soil use and restoration. The proposal includes mandatory monitoring of land take and soil sealing by Member States, to be conducted according to a common framework of indicators and methodological criteria (). The proposed indicators include total artificial land; land take, including reverse land take (i.e., the renaturalization of previously developed land); net land take (i.e., total minus reverse land take); and soil sealing. Member States may also measure optional indicators such as land fragmentation, land take for specific uses, and impacts on ecosystem services. According to the Commission's proposal, the monitoring of soil sealing and land take indicators should be conducted at least annually.

The "no net soil sealing and increase the reuse of urban soils" objective is linked to several other strategies, goals, and targets of the EU, including those of the Roadmap to a Resource Efficient Europe () (which included especially the no net land take by 2050 target), the EU Biodiversity Strategy to 2030 (), the Nature Restoration Regulations (), and the EU Action Plan "Towards Zero Pollution for Air, Water and Soil" (). Achieving "no net soil sealing and increase the reuse of urban soil" would also contribute to other EU Missions and related policy areas, such as Oceans, Seas and Waters (management of water quality and quantity in urban areas), Adaptation to Climate Change (flood mitigation), and Climate Neutral and Smart Cities (climate mitigation and resource efficiency). In addition, the objective is directly linked to several targets of SDG 11 - Make cities and human settlements inclusive, safe, resilient and sustainable and SDG 15.3 – End Desertification and Restore Degraded Land.

This document provides an overview of the state of knowledge related to this objective, by identifying specific knowledge gaps, actions to address them and potential bottlenecks. This document was prepared by the members of the "Soil sealing and urban soils" Think Tank within the SOLO project, through the process illustrated in.

Table 1. Definitions.

Soil is the upper layer of the earth in which plants grow (Nougues and Brills 2023).
Land is the ground, including the soil covering and any associated surface water, over which ownership rights are enforced (Nougues and Brills 2023).
Soil sealing is the loss of soil resources (nutrients and moisture) due to the covering of the soil surface with impervious materials, as a result of urban development and infrastructure construction (https://esdac.jrc.ec.europa.eu/themes/soil-sealing).
Land take is the conversion of natural and semi-natural land into artificial land (Soil Monitoring Law - Article 3 (European Commission: Directorate-General for Environment 2023). Land take is a process that transforms natural and semi-natural areas (including agricultural and forestry land, gardens and parks) into artificial land (e.g., residential and industrial areas), using soil as a platform for construction and infrastructure as a direct source of raw material, or as an archive for historic patrimony. This transformation may cause the loss, often irreversibly, of the capacity of soils to provide other ecosystem services (provision of food and biomass, water and nutrients cycling, basis for biodiversity and carbon storage). (Soil Monitoring Law - Preamble (30), European Commission: Directorate-General for Environment 2023).
Soil reuse involves the repurposing of excavated soil from construction sites, which may be reused on-site or off- site, taking into account its characteristics and ensuring that they are compatible with the new soil application (Hale et al. 2021).
Land recycling is defined as the reuse of abandoned, vacant or underused land for redevelopment (European Environment Agency 2021).

DOI: 10.5281/zenodo.17430539

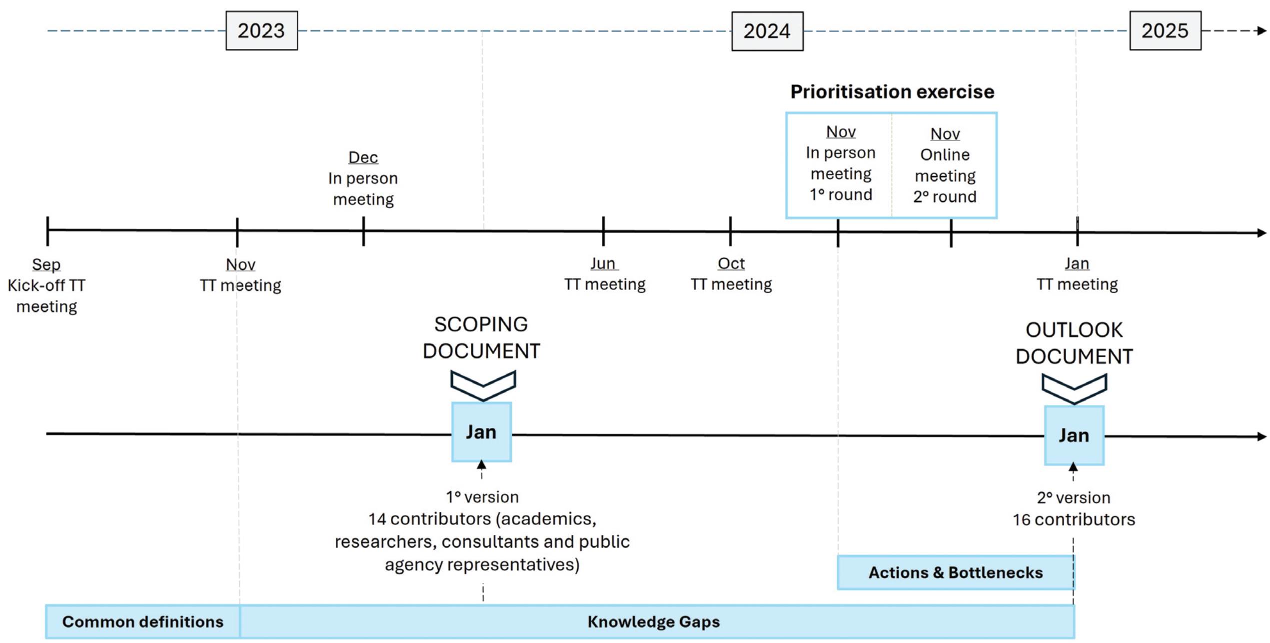

Figure 1. Timeline and main activities of the "soil sealing and urban soils" Think Tank.

List of abbreviations

EU - European Union
SOLO - Soils for Europe Project

State-of-the-art

Fig. 2 illustrates the link between the two topics that form the objective, namely soil sealing and soil reuse. The next sub-section presents an overview of the state of the art for each of them.

Soil sealing

Despite being among the human activities with the greatest impacts on soil, data on sealing at the European level were lacking for a long time. In the past three decades, the extent of soil sealing has been estimated based on land take data, also reflecting the greater policy attention dedicated to the latter process, for which the "no net" target had been proposed already in 2011 (European Commission 2011).

At the EU level, the main land uses that generated land take during 2000-2018 were industrial and commercial, as well as extension of low-density residential areas and construction sites (European Environment Agency 2019). Most of the new land take was at the expense of agricultural soils, often highly fertile soils located in flat areas where cities have historically developed. As a result, the negative effects on ecosystem services are significant (European Environment Agency et al. 2022). More detailed data on land take and net land take are available at the level of individual cities and commuting zones based on the Urban Atlas database, which provides high-resolution land use land cover maps of 788 Functional Urban Areas (FUA), i.e. cities and related commuting zones, across Europe (European Environment Agency 2023). However, the fact that this database does not cover the area outside functional urban areas of the EU limits its application for large scale (national and continental) monitoring.

In 2018, the Copernicus Land Monitoring Service (CLMS) released the Imperviousness Density (IMD) layer, a high-resolution raster map capturing the spatial distribution and changes of artificially sealed areas across the EEA-38 countries and the UK. While the IMD maps provide a homogeneous dataset for assessing soil sealing at the EU level, the change from the 20m resolution of the older maps (2006-2015) to the 10 m resolution of the newer maps (starting 2018) disrupted the consistency of the temporal series.

DOI: 10.5281/zenodo.17430539

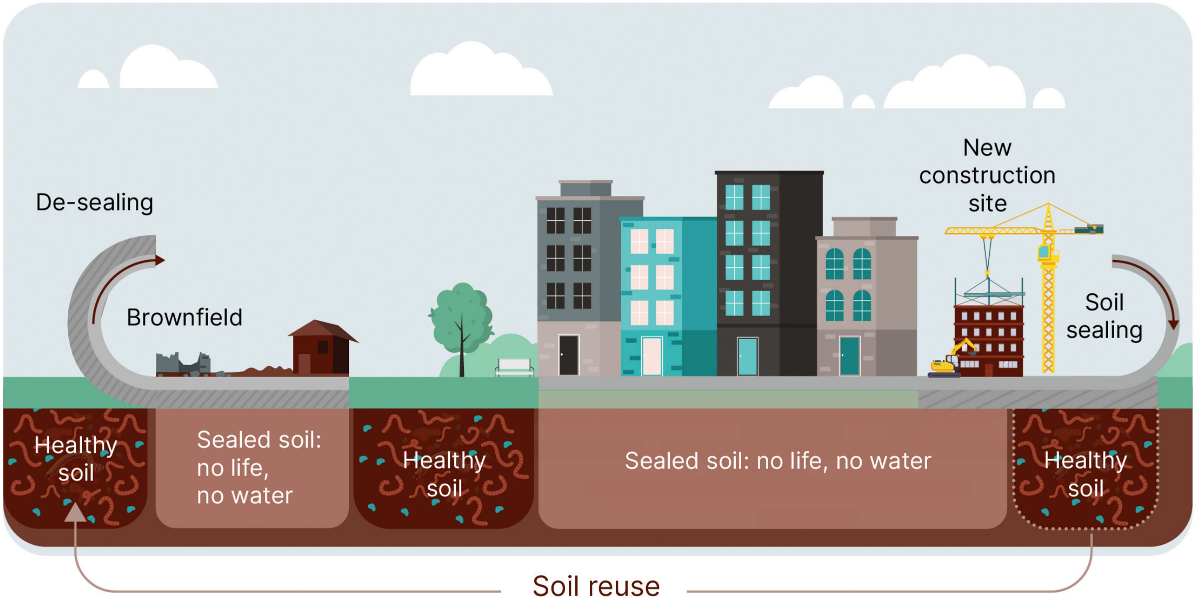

Figure 2. Illustration of the Think Tank topics and their relationship.

The CLMS has recently released a harmonised IMD time series that overcomes the challenge of the mentioned resolution change and documents sealed cover evolution in a robust way. In addition to the IMD series, CLMS has produced the CORINE Land Cover (CLC) + Backbone Raster dataset for the years 2018 and 2021, which includes a thematic sealed class. The CLC+ Backbone represents a major improvement over the previous CORINE Land Cover system, offering enhanced land cover classification into 11 basic categories and a more robust framework for monitoring soil sealing across the EU (Maucha et al. 2024). However, the temporal coverage is limited and discrepancies remain, as the IMD dataset tends to underestimate sealed areas compared to CLC+ Backbone and reference datasets (Sannier et al. 2024). Moreover, it is important to note that both datasets estimate sealing based on remote sensing data. This data only captures surface sealing and does not account for underground structures, such as basements and parking garages, because these are not visible through remote acquisitions. These types of structures are common in urban areas and contribute to the reduction of soil ecosystem services like water infiltration and purification (Tobias et al. 2018).

The description of the specific objective of "no net soil sealing and increase the reuse of urban soils" contained in the Soil Mission also mentions the increase of land recycling activities (European Environment Agency 2016). The term "land recycling" refers to the reuse of previously built-up or artificialised land (abandoned, vacant or underused land) for redevelopment. Land recycling was captured by one of the indicators developed by the EEA to monitor specific processes linked to land take. The land recycling indicator includes three components: "green recycling", "grey recycling", and "densification" which were assessed for the first time by the EEA in 2016 based on Urban Atlas data. Densification is defined as "land development within existing urban areas that makes maximum use of the existing infrastructure" (European Environment Agency 2021), thus minimising new land take and soil sealing. Between 2006 and 2012 densification accounted for the largest proportion of land recycling (9% of total land consumption*[1]). Grey recycling, i.e., the internal conversions between residential and/or nonresidential land cover types, was secondary

DOI: 10.5281/zenodo.17430539

to densification (3.2% of total land consumption), with country rates ranging from 14% of total land consumption in Latvia to less than 1% in Slovakia, Slovenia, Luxembourg, and Lithuania. Green recycling, i.e., the development of green urban areas on previously built-up areas, including desealing activities, was a marginal process in all countries and, on average, accounted for only 0.2% of total land consumption between 2006 and 2012. The monitoring of these indicators by the EEA was discontinued, so more recent figures are not available. The Soil Mission has set a target of exceeding the value of 13% for land recycling. This figure refers to the period of 2006-2012, when land recycling contributed only 13% of the total land use changes involving urbanised areas in European FUAs.

The gaps identified in addressing soil sealing and land take highlight the necessity for cohesive and effective policies. Challenges include fragmented legal systems, as well as the difficulties in designing and implementing regulatory, fiscal, and incentive-based instruments (Ronchi et al. 2019). Urbanisation continues to cause land take, impacting biodiversity and ecosystem services. Public acceptance of no net soil sealing policies is hindered by limited awareness of soil functions and trade-offs between environmental goals and material welfare (Teixeira da Silva et al. 2018), with policies often overlooking socio-economic effects like housing affordability, urban congestion, and inequalities between landowners and non-owners (Vejchodská et al. 2022). There is a need for tools to support a better integration of soil health and soil ecosystem services into spatial planning processes (Calzolari et al. 2020), and of socially balanced policy tools to achieve the no net soil sealing target in a sustainable and equitable way.

Urban soil reuse

In most countries, soil excavated from construction sites is currently considered as waste and disposed in landfills, which makes it the biggest source of waste in the EU (more than 520 million tons only in 2018) (Scialpi and Perrotti 2022). To reduce this trend, the Soil Strategy aims to investigate the streams of excavated soils and considers proposing a “soil passport”, on the model of existing digital tools to track soil reuse in some EU countries (e.g., in Belgium and under development in France) (SOILveR (Soil and land research funding platform for Europe), 2022). These tools are sometimes also called or linked to ‘soil banks’, whose aim is to reconcile supply and demand of surplus soil from construction sites.

The legal frameworks on excavated soils and their potential reuse differs across Member States (European Commission: Directorate-General for Environment et al. 2024). In some countries, reuse is encouraged and even enforced for certain soils of high agricultural value. In other countries, reuse is allowed under certain conditions that usually refer to the quality of the soil and sometimes set temporal and spatial boundaries for the new application (e.g., in Sweden, reuse is allowed only on-site and within a reasonable period of time) (Hale et al. 2021). Often, additional permits or licenses are required, which impose a burden on reuse activities (Hale et al. 2021).

The management of excavated soils and their potential reuse is strictly linked to the issue of pollution (addressed by the fourth specific objective of the Soil Mission), although only part of excavated soil is polluted. While potentially contaminated sites in EEA-39 amount to 2.8 million, diffuse pollution (including pollution due to microplastic) could be a major problem in urban soils, whose impacts are still largely unknown. Beyond these general issues, other local issues may emerge in specific contexts as an effect of the high levels of soil sealing and associated anthropic activities and management practices, including compaction, erosion, and other types of concentrated pollution, which may affect urban soils in different ways compared to natural soils.

A detailed knowledge of the quality of soils, not only in terms of contamination levels but also in terms of geotechnical properties, is a prerequisite for safe reuse (Hale et al. 2021). The current level of knowledge on urban soils is generally poor, also due to the high spatial variability of their properties (Pouyat et al. 2020). The LUCAS topsoil survey is the only database that provides soil properties from samples collected across the EU (Eurostat 2018), although it is important to note that the parameters measured in urban

DOI: 10.5281/zenodo.17430539

areas differ from those assessed in other land use categories. The Soil Monitoring Law includes measures to enhance the role of LUCAS by increasing the density of sampling points. However, more and more databases of urban soil quality are being developed at the regional level (e.g., the GeoBaPa in the Regions Ile de France and in Normandy, or similar examples in various Länder in Germany) and even at the national level (e.g., BDSolU in France).

Prioritisation of knowledge gaps

The initial list of knowledge gaps in the Suppl. material 1 was developed through a scoping review of relevant literature and refined through discussions within the Think Tank. Once consensus had been reached, a two-round prioritisation exercise was conducted. During the general project meeting in Sofia, Bulgaria (November 2024), Think Tank participants voted on the ten most relevant gaps. In the first round, all meeting attendees, including members from all SOLO Think Tanks, selected their top three gaps from this list. A second round was later conducted online to include those who were unable to attend in person. Final scores were calculated by summing the votes from both rounds. Table 2 presents the top 10 gaps. The following section details the state of the art for the top three gaps and provides an overview of the other priority gaps identified by the Think Tank members.

Roadmap for “No net soil sealing and increase the reuse of urban soils” Think Tank

Key knowledge gaps

New policy approaches and instruments to reduce soil sealing

At the city level, the issues of soil sealing and land take are primarily addressed in spatial planning processes. During these processes, goals and strategies for urban development are defined and policy instruments are identified to implement them. Policy instruments at the city level can be broadly categorised into binding and non-binding instruments. Binding instruments include specific regulatory measures such as quantitative soil sealing targets, restrictions on developing existing green areas, zoning of agricultural priority areas, and limitations on specific types of developments. For instance, zoning regulations typically establish acceptable limits on soil sealing for different land uses and implement enforceable rules to safeguard natural resources (Redon and Mialot 2024). A relevant example can be found in the city of Eindhoven, which introduced the new Environmental Planning Act, known as the ‘Omgevingswet,’ in 2019. Non-binding instruments include, among others, strategic planning documents, and incen-

Table 2. Ranking of the top 10 knowledge gaps identified (a full list of all identified knowledge gaps is given in the Suppl. material 1). Type of knowledge gap: KDG = knowledge development gap, KAG = knowledge application gap.

Rank	Knowledge gap	Type of knowledge gap
1	New policy approaches and instruments to reduce soil sealing	KDG
2	Best practices to promote the reuse of urban soils from construction sites	KAG
3*	Effectiveness of desealing interventions	KDG
3*	Legal and regulatory dimension of soil sealing	KDG
5	Socio-economic impacts of no net soil sealing policies	KDG
6	Minimum unsealed soil per person to ensure biodiversity and human health in urban areas	KDG
7	Drivers of soil sealing from individual to sectoral policies	KDG
8	Typologies of soil sealing and their impact on soil functions and services	KDG
9	Acceptability and legitimacy of no net soil sealing policies	KDG
10	Links between soil sealing and land take	KDG

DOI: 10.5281/zenodo.17430539

tive-based instruments designed to guide and encourage sustainable land use without imposing mandatory requirements (Naumann et al. 2018). The implementation and effectiveness of instruments can differ due to various factors such as bureaucratic complexity, inadequate monitoring, limited human or financial resources, conflicting interests, counter-incentives, lack of enforcement, political issues, and the absence of regional contextualisation.

Across Europe, the presence and enforcement of land take policies vary significantly. Countries such as Estonia, Poland, and Czechia lack explicit policies limiting land take. In contrast, Germany, Italy, Belgium, and Switzerland have adopted national goals, which are then implemented at the regional level. However, in Italy and Germany, these goals are not legally binding but instead serve as aspirational targets (D'Ascanio et al. 2024). France set national goals of a 50% reduction in all the land use processes occurring on or ending up in developed land, which apply to the whole of France and uniformly to each region and Luxembourg set these goals at the local level. Generally, reducing land take is a widely debated topic, while soil sealing has emerged more recently (D'Ascanio et al. 2024). Few countries have adopted fiscal policies to prevent soil sealing, and those that have implemented these measures typically sets uniform thresholds without consi dering the local context, thereby undermining the policy'sits effectiveness (Ronchi et al. 2019). Instruments based on financial charges or incentives are rare and, when introduced, are seldom applied comprehensively (Vejchodská and Pelucha 2019). For example, Austria and Germany provide financial incentives for the reuse of brownfields and for desealing measures. Belgium has introduced fiscal measures that incentivise demolition and reconstruction projects to encourage urban regeneration. Similarly, the French government has established a "brownfield fund" to financially support both private and public redevelopment of brownfield sites (D'Ascanio et al. 2024). In the United Kingdom, authorities are actively promoting the economic redevelopment of brownfield sites for residential purposes while also allowing controlled development on greenfield sites (Build Europe 2022). Although these measures show potential, their scale and scope remain limited, restricting their broader impact. This underscores the urgent need for more tailored, evidence-based policy instruments that address local environmental, social, and economic conditions.

A key principle in designing land policy instruments should be the mitigation hierarchy, which prioritises actions based on their impacts. The hierarchy includes a sequence of approaches, ranging from avoidance of land take and soil sealing to mitigation of their effects, and finally to compensation and restoration of degraded land (European Commission: Directorate-General for Environment 2021). Ideally, policy instruments should be aligned with this hierarchy to achieve specific outcomes (European Commission: Directorate-General for Environment 2012). Particularly:

- Avoidance: instruments aimed at avoiding land take should focus on preventing new greenfield developments. Protective measures, such as zoning agricultural priority areas or imposing restrictions on greenfield developments, are crucial in achieving no net land take.
- Mitigation: policies that mitigate the negative impacts of soil sealing, such as requirements for permeable surfaces in urban areas or water management systems, help address the environmental consequences of urbanisation.
- Compensation: instruments designed to restore land and ecosystems, such as mandatory reforestation.
- Offset (compensation): redevelopment of abandoned urban areas into new green areas can compensate for unavoidable impacts.

Effective policies should align with the mitigation hierarchy to balance development needs and environmental sustainability. For instance, development instruments should prioritise grey and green recycling and brownfield redevelopment to achieve 100% land recycling in the long-term, minimising the need for new greenfield projects (Lacoere and Leinfelder 2023). To achieve the ambitious no-net targets, a single instrument is insufficient, and a policy

DOI: 10.5281/zenodo.17430539

mix of various instruments is necessary (Spyra et al. 2025). There is a lack of integration among different policy instruments.

Designing effective land policy instruments is a complex process, requiring innovative approaches that balance competing public and private interests. One such approach could be the combined use of compensation and incentive mechanisms. These mechanisms address both the costs of inaction (push factors) and the benefits of sustainable soil use (pull factors), creating a dual approach to promote better land management. For example, developers could be required to compensate for soil sealing by investing in restoration projects, while also receiving incentives for adopting sustainable practices. Another innovative approach involves integrating soil functions and ecosystem services into the assessment of compensation measures (Calzolari et al. 2020), thus making explicit the value of soil and of its ecological benefits. For instance, incentives could be linked to preserving or enhancing ecosystem services such as carbon storage, water filtration, or biodiversity (Jost et al. 2021). By valuing these services, policies can encourage sustainable soil use while discouraging practices that degrade soil quality. Tradable permits could also be considered a promising economic policy instrument aimed at reducing land take, still lacking large scale implementation (Henger et al. 2023).

The specific questions associated with this gap are:

1. What types of policy instruments proved to be effective in supporting the no net soil sealing target in different contexts?
2. What innovative instruments and policy mixes can be designed to achieve the no net soil sealing target?

Best practices to promote the reuse of urban soils from construction sites

In a rapidly urbanising world, the importance of urban soil quality has grown significantly (Burghardt et al. 2022, Lehmann and Stahr 2007). Soil quality refers to the capacity of soil to function within ecosystems, supporting biological productivity, maintaining environmental quality, and promoting the health of plants, animals, and humans (Tresch et al. 2018). Urban soils, however, differ substantially from natural soils due to their altered physical, chemical, and biological characteristics caused by human activities (Kim et al. 2021, Pavao-Zuckerman 2008). Rapid urbanisation increases construction and demolition activities, generating large volumes of excavated soil (Hale et al. 2021). An example of these activities is road construction. Between 2012 and 2018, 189 km² of agricultural and natural land was converted in the EU for the expansion of the transport network (Damme and Keller 2023). The reuse potential of excavated soils depends on their geochemical compatibility with the receiving site (Sauvaget et al. 2020).

The excavated soils that cannot be reused on-site are classified as waste and managed under national policies. Member States have developed distinct regulations for the reuse of soil, leading to significant variation across countries. For example, in France, guidelines require contamination assessments for excavated soils. If the soil is contaminated, it must be treated or transported as waste. Non-contaminated soils, however, can be reused provided they meet geotechnical requirements. In Norway, surplus excavated soil is also classified as waste, with threshold values used to distinguish clean from contaminated soils. Sweden, by contrast, does not classify excavated soil as waste if it is reused on the same site within a reasonable timeframe (Hale et al. 2021). Despite these efforts, there is no unified European framework with standard regulations and threshold values for excavated soils, leaving soil reuse to be governed by national policies (Blanc et al. 2012, Hale et al. 2021).

The European Soil Strategy (European Commission: Directorate-General for Environment 2021) has proposed investigating excavated soil streams and assessing the feasibility of a “soil passport” or digital tracking system to enhance circular economy efforts. This initiative aims to promote the safe reuse of clean soils in all Member States. Some countries

DOI: 10.5281/zenodo.17430539

have already implemented soil passport systems. For example, Flanders in Belgium has incorporated soil passports into its contamination legislation, while Austria operates a similar system. In France, a national regulatory traceability system is in place for excavated soils, while in the UK, the Definition of Waste: Code of Practice (DoW CoP) outlines processes for reusing excavated materials on-site or moving them between sites. Digital tools, such as the TERRASS database, provide interactive online systems for monitoring soil quality and reuse (Blanc et al. 2012). However, there remains a critical lack of standardised indicators, protocols, methods, and tools for assessing urban soil quality and tracking its movement, making it difficult to implement these solutions (Llatas 2011, Ittner and Naumann 2022). In addition, tools to analyse soil quality and monitor its movement through a standardised "soil passport" system are still underdeveloped (Ittner and Naumann 2022, SOILveR (Soil and land research funding platform for Europe 2022).

Many European Member States have proposed measures and set targets to increase the recovery and reuse of construction and demolition waste, but these initiatives often lack clarity regarding their implementation, especially for excavated soils (European Commission: Directorate-General for Environment et al. 2024). For instance, Estonia has set a target of recovering more than 75% of construction and demolition waste, though it is unclear whether this includes soil. Hungary is preparing legislation to establish a waste transfer system, which will include collection points and incentives for reusing and recycling construction waste. In Finland, the city of Helsinki has initiated a project to optimise the reuse of excavated soil within urban construction projects. While government-funded initiatives dominate efforts to promote soil reuse, the private sector has started to contribute in some cases, as demonstrated by the Helsinki project (European Commission: Directorate-General for Environment et al. 2024).

Despite progress, significant gaps remain in the development of cohesive European policies and best practices to promote soil reuse. The limited coordination between Member States and the absence of harmonised regulations exacerbate these challenges. Furthermore, current initiatives often fail to account for local contexts, resulting in less effective implementation. Addressing these issues requires a unified European framework that includes standard guidelines and evaluation metrics. To overcome these challenges, it is crucial to implement evidence-based, context-specific policies supported by robust tools and monitoring mechanisms. By promoting cohesive strategies, fostering collaboration between the public and private sectors, and raising awareness of the benefits of sustainable soil management, governments can advance the circular economy and ensure better urban soil management.

The specific questions associated with this gap are:

1. What are existing best practices of certifying soil quality and tracking soil transportation ("soil passport")? How could they be scaled at the EU level?
2. What are the most effective policy instruments to promote the reuse of urban soils?

Effectiveness of desealing interventions

Desealing is the process of removing artificial, impervious structures such as roads, buildings, and parking lots to restore soil permeability and, ideally, its ecosystem services. In many countries and regions, desealing actions are being proposed as a means of adapting urban areas to climate change, thus contributing to urban resilience. The amount of unsealed area, soil quality, and urban green infrastructure are used to map urban environmentally sensitive areas, which play a crucial role in maintaining ecological balance (Sobocká et al. 2020). Besides restoring permeability to improve rainwater management and reduce urban heat, desealing interventions may also promote biodiversity and the provision of other ecosystem services, particularly if desealed patches are sufficiently large and well connected.

DOI: 10.5281/zenodo.17430539

It is important to acknowledge that desealed soils are anthropogenic and often exhibit reduced multifunctionality compared to undisturbed soils. Using agricultural topsoil for restoration is a common practice, but it is not environmentally sustainable as it implies the extraction and relocation of high-quality soil from rural to urban areas. Indeed, research shows that desealed soils can, in some cases, regain their biological quality and fertility without needing additional topsoil (Maienza et al. 2021). Studies on the effectiveness of desealing in restoring soil functions in the long term are limited (Tobias et al. 2018) and many desealing projects lack systematic evaluations of their environmental and social benefits (Vieillard et al. 2024). As an exception, the PermèaSoil project (https://www.strasbourg.eu/permeasol) provided valuable insights into the potential benefits of desealing. Over a three-year period, researchers observed the ecological development of desealed urban soils. Initially, these soils exhibited minimal organic matter, low biological activity, and an absence of vegetation. However, vegetation began to emerge within just one month, including both pioneer species and plants adapted to asphalt environments. Following the removal of impervious surfaces, water infiltration rates improved significantly, and over subsequent months, increases in water storage and organic matter content were anticipated.

Estimating the potential recovery of soil functions after desealing and the benefits generated in different contexts can help prioritise interventions. For example, areas with higher potential for restoring permeability, fertility, or biodiversity may be given precedence in urban planning efforts. At the regional level, urban population dynamics - whether a region is experiencing growth or decline - should also be considered. Research suggests a possible correlation between population growth and the extent of soil sealing, emphasi szing the need for tailored desealing strategies that account for these variables (Colsaet et al. 2018). For shrinking regions, desealing interventions may focus on reclaiming unused or abandoned spaces, restoring natural functions, and promoting ecological resilience (Decoville and Feltgen 2025). Rapidly growing urban areas may prioritise desealing as a means of mitigating risks such as flooding and heat stress. Despite these considerations, there remains a need for more rigorous and standardised methodologies to identify suitable areas for desealing. Establishing clear criteria for prioritising interventions will ensure that resources are allocated effectively and that desealing projects achieve their intended outcomes (Ittner and Naumann 2022). Cost-benefit analyses that also consider energy input required, CO_2 emissions, and waste produced could be a valuable support in prioritising interventions.

The specific questions associated with this gap are:

1. How effective are desealing/unsealing actions in restoring soil functions and services?
2. What is the potential for desealing in different contexts (urban vs. non-urban areas, different types of settlements)?
3. How do weto identify and prioritise suitable areas for desealing interventions based on their environmental and social impact?

Legal and regulatory dimension of soil sealing

To gain a deeper understanding of soil, it is important to consider both its environmental dimension, which is in constant interaction with the natural world, and the dimension of private property along with all its associated rights. These elements are interrelated and play a crucial role in how soil issues are understood and legally addressed (Fox 2024, Gradinaru et al. 2023).

The definition and regulation of soil vary significantly across EU Member States, reflecting the diverse legal frameworks of each country (Kaplinsky 2023). This diversity has led to a fragmented approach to soil governance, with little coherence across national borders (Ronchi et al. 2019). Few national governments have implemented comprehensive strategies to address issues such as urbanisation, land take, and land use changes. The EU's target of achieving no net land take by 2050, launched in 2011, was an ambitious goal supported by non-binding measures, such as the "Guidelines on Best Practices to Limit, Mitigate, or Compensate Soil Sealing" (European Commission:

DOI: 10.5281/zenodo.17430539

Directorate-General for Environment 2012). However, progress has been limited due to the lack of enforceable actions. Similarly, the target of no net soil sealing requires supportive legislation. The Strategic Environmental Assessment (SEA) and the Environmental Impact Assessment (EIA) are promising legal instruments that can encourage the consideration of environmental impacts of plans and projects by promoting the identification of more environmentally friendly alternatives, hence contributing to a more systematic and transparent planning process to curb land take and soil sealing (Schatz et al. 2021).

Some Member States have taken significant steps toward soil conservation, but the approaches differ substantially. Ronchi et al. provide a review of instruments for soil protection across EU member states (Ronchi et al. 2019). In Austria, federal planning laws address soil protection, particularly in the state of the Land Salzburg. Belgium's Wallonia region has adopted an Agricultural Code (2014) that identifies soil as a natural resource requiring protection from urban expansion. Local legislation encourages limiting soil sealing through measures such as rules for water management systems and filtering plants, which help reduce surface runoff and overflows. Additionally, federal urban planning instruments aim to regulate land use changes, fostering greater sustainability and mitigating land take. Luxembourg offers another example of integrated soil conservation policies. The "Law Concerning the Evaluation of the Environmental Impacts of Certain Plans and Programmes" acknowledges the direct influence of planning instruments on soil health. Since 2003, the country has implemented a Master Programme for Spatial Planning, which outlines long-term strategies for protecting soil functions and promoting sustainable resource management. This programme coordinates various planning levels (regional, local, and sectoral) while addressing transport systems, infrastructure, and urban development to curb soil sealing and safeguard the natural environment. While these examples illustrate progress, the legal frameworks governing soil sealing and urban expansion remain inconsistent across Member States. The diversity of approaches underscores the pressing need for a unified European approach to ensure cohesive soil management practices.

One area requiring particular attention is the legal treatment of property rights, which significantly influences soil use and conservation. Property rights are central to land management, encompassing ownership by individuals, groups, or entities such as the state. These rights can be classified as private, common, or public and determine the permissible actions on land and soil (Lawry et al. 2014). However, the current property rights regime often limits public authorities' ability to impose stricter regulations on land take and urbanisation. For example, in Romania, a country where property rights are strong, authorities have a hard time rejecting requests for building permits aimed at the development of residential areas, even on fertile soils (Gradinaru et al. 2023). Property rights are a complex issue in soil management, particularly in urban contexts. While they have been widely discussed in the agricultural sector (Amentae et al. 2024), their implications for urban soil conservation remain underexplored. Development rights, often granted to private property owners, can constrain public sector interventions aimed at limiting soil sealing. There is growing recognition that private property rights should come

with social obligations, such as the duty to manage soil sustainably. However, the current legal frameworks do not adequately incorporate these responsibilities (Halleux et al. 2012). For example, landowners are rarely required to account for the environmental impacts of soil sealing or urban expansion. Strengthening the legal framework to emphasisze these social obligations is essential for advancing sustainable soil management and achieving the EU's no net land take goal.

The specific questions associated with this gap are:

1. How does the legal dimension of soil sealing and land take vary across Member States and what are the opportunities and challenges to integrate the no net soil sealing objective?
2. How do property rights and property regimes affect soil sealing?

DOI: 10.5281/zenodo.17430539

Prioritised knowledge gaps

Socio-economic impacts of no net soil sealing policies

The policies of no net soil sealing and no net land take have both positive and negative impacts on society. The positive aspects include the enhancement of people's health and well-being and the long-term sustainability of human development. The negative aspects include significant adverse impacts on individual material welfare: decreased housing affordability and, as a result, higher urban rents due to the increased scarcity of land allocated for housing development (Vejchodská et al. 2022). Increased congestion after the densification of cities, and consequently, a decrease in quality of life, have also been mentioned as potential negative effects (Decoville and Feltgen 2023), which trigger resistance from residents to further construction as they seek to protect natural resources and preserve social harmony (Götze and Hartmann 2021). Exacerbated income and wealth inequality between different societal groups (the owners and non-owners of urban land) might be another outcome of higher scarcity of urban land. There is a significant knowledge gap in how to design public no net soil sealing policies that effectively minimise these adverse impacts.

Addressing these challenges will require the integration of different types of policies including fiscal instruments, such as property taxes, jointly with specific planning and land policies. A theoretical/analytical framework is needed to qualify policy measures according to their ability to reduce land take and sealing while minimising the risks of exacerbating socio-spatial injustices, depending on each region's spatial/demographic/economic context.

The specific questions associated with this gap are:

1. Which instrument mixes should be to applied in different institutional settings for minimising the negative impacts of no net soil sealing and no net land take policies on housing affordability and other areas of material welfare?
2. How to ensure that policies aimed at halting land take and soil sealing do not exacerbate inequalities?

Minimum unsealed soil per person to ensure biodiversity and human health in urban areas

The rate of soil sealing in urban areas has a significant impact on both biodiversity and human health. Sealed surfaces significantly reduce the richness and abundance of various species by limiting habitat availability and disrupting ecological balance. For instance, Yan et al. (2019) found that in Wuhan, plant diversity sharply declines when impervious surfaces exceed a threshold of 40–60%. Additionally, the increase in sealed surfaces leads to a greater proportion of exotic plants, which can be detrimental to native biodiversity. The authors recommend keeping the share of soil sealing below 40% in cities to help preserve urban biodiversity.

In addition to biodiversity, the demand expressed by the population for the numerous ecosystem services provided by unsealed soils could be used as a basis to define minimum rates of unsealed surfaces to maintain in urban areas. For instance, green spaces promote well-being through cultural benefits such as beauty, inspiration, and belonging (O'Riordan et al. 2021). Various studies (Jungels et al. 2013, Rugel 2019) demonstrate the positive impact of visible greenery on mental health and well-being. Recently, the "3-30-300 rule" has been proposed as a set of specific targets to ensure residents have adequate access to nature and can enjoy the benefits of natural environments. These targets include the ability for everyone to see at least three mature trees from their home, workplace, or school, a minimum of 30% tree canopy cover in their neighborhood, and living within 300 meters of a high-quality public green space that is at least 0.5 hectares in size (Konijnendijk 2021). As shown by this simple rule, the benefits are not just a matter of total amount of green spaces or unsealed soil, but also of its spatial distribution, which should ensure equal benefits for all. Similar thresholds to steer spa-

DOI: 10.5281/zenodo.17430539

tial planning decisions could be developed having soil sealing and its impacts in mind.

The specific questions associated with this gap are:

1. What is the minimum area of unsealed soil needed in urban areas to effectively support biodiversity?
2. What is the minimum area of unsealed soil per person required in urban areas to promote human health and well-being?

Drivers of soil sealing from individual decisions to sectoral policies

Spatial planning is a primary factor determining soil sealing and land take, as decisions on urban expansion, densification, regeneration, and greening shape land use changes. Different spatial planning strategies impact soil sealing and land take in various ways: densification can limit urban expansion and reduce land take but may increase soil sealing in urban areas, while greening and nature-based solutions can promote desealing but might require new land take. For example, despite efforts toward sustainable urban development, only very few European cities have successfully halted land take between 2006 and 2012, with some paradoxical trends. In fact, growing cities densified but expanded inefficiently through abandonment of urbanised areas and fragmentation, while most shrinking cities increased residential areas despite population decline (Cortinovis et al. 2019). Evaluating the combined effects of multiple strategies is therefore critical to achieving no net land take and no net soil sealing targets.

Beyond spatial development policies, it is crucial to capture the impact of sectoral policies that can generate high demand for land. Sectors like tourism (Kizos et al. 2017), transport infrastructure (Oliveira et al. 2018), and commerce (Munafò 2023) contribute significantly to soil sealing and land take. Tourism demands facilities, roads, and parking, while transport and commercial developments, such as logistics hubs, exacerbate land take. These are often deemed activities of "public interest," hence they bypass standard planning regulations, as seen in Italy, where logistic hubs have significantly contributed to land take and soil sealing in recent years, even in regions where targets are in place (Munafò 2023). Addressing the impacts of these sectoral policies requires tailored protocols.

Individual decisions also play a role in soil sealing (Künzel et al. 2024). Landowners and land managers influence sealing rates within private areas, and while differences exist across Europe, the social, economic, and cultural drivers of these decisions remain underexplored (Bouma 2018). Understanding these drivers is crucial for formulating effective strategies to mitigate soil sealing and land take. In conclusion, achieving no net land take and soil sealing targets demands a multifaceted approach that integrates spatial planning with assessments of sectoral policies and individual decision-making processes.

The specific questions associated with this gap are:

1. What is the impact of different spatial planning strategies (e.g., densification, regeneration, greening) on soil sealing and land take?
2. What other sectoral policies have an indirect impact on soil sealing and land take? How do we ensure that this impact is considered in their evaluation?
3. What social, economic, and cultural factors drive soil sealing decisions by landowners and land managers?

Typologies of soil sealing and their impact on soil functions and services

The EU Soil Mission defines soil health as the continued ability of soils to support ecosystem services (European Commission: Directorate-General for Research and Innovation 2022). Soil sealing compromises the functions of soils and, consequently, their ability to provide ecosystem services (Tóth et al. 2022). However, unsealed soil does not necessarily mean healthy soil. In urban areas, other processes may impair

DOI: 10.5281/zenodo.17430539

the capacity of soil to provide ecosystem services. For example, compaction may limit water infiltration. Hence, a more in-depth analysis of soil characteristics, and of their contribution to soil health, is needed to overcome the simplistic “sealed vs unsealed” classification (Decoville and Schneider 2016, Drobnik et al. 2018).

Examples of approaches that include the analysis of soil properties and functions exist in both literature and practice. Several studies have assessed soil health using a variety of indicators and methods, such as the Soil Assessment System that assigns different weights to individual soil characteristics, including texture, humus content, and depth of soil horizon (Toth et al. 2023). Studies like these can be used as a starting point to develop and test approaches that offer more insights into actual soil health. For example, in Sweden, the Biotope Area Factor was designed to enhance microclimate and air quality, protect soil function, improve water management efficiency, and increase habitat availability for plants and animals (Stange et al. 2022).

A specific challenge to be addressed by these new approaches is the treatment of underground processes of soil sealing, and their impacts on soil properties and functions (Tobias et al. 2018). These include, for example, the construction of underground parking places in residential developments, which are covered by green areas. The challenges include developing operational methods to assess the impacts of these processes on soil health, as well as mapping and inventorying them.

The specific questions associated with this gap are:

1. What are the most suitable methods and indicators to assess the impacts of soil sealing on key soil functions and services?
2. How can we operationally transition from the “sealed vs. unsealed” classification towards a more detailed assessment based on key soil properties? How can this be used to support the design of innovative no net soil sealing policies?
3. How can underground soil sealing be assessed?

Acceptability and legitimacy of no net soil sealing policies

Societal acceptance and acceptability are key aspects in promoting policies related to no net soil sealing and no net land take. Acceptance refers to the response following the implementation of a policy, while acceptability pertains to favorable or unfavorable perceptions prior to any policy interventions (Dreyer and Walker 2013). Societal support is essential as, without it, policymakers are often hesitant to enact tangible measures. This reluctance of public authorities to take decisive action is a significant factor contributing to the failure of environmental policies (Zvěřinová et al. 2014). At the local level, land take is often viewed positively, yet the relationship decision-makers have with this concept has not been thoroughly examined (Gradinaru et al. 2023).

Improving the social acceptability of no net soil sealing and no net land take policies is therefore crucial (Decoville and Feltgen 2025). A factor that highly affects social acceptance and acceptability of such policies is their impact on the material welfare of individuals, such as housing affordability or the decrease in quality of living due to densification (discussed in socio-economic impacts of no net soil sealing policies).

Citizens’ awareness of the impact of soil sealing and mitigation strategies is another factor affecting social acceptability.

At the individual level, acceptability is influenced by various socio-economic factors, such as income, nationality, education, personal experiences, and environmental knowledge (Vanino et al. 2022). The latter is linked to the awareness of soil multiple functions, hence to the level of soil literacy in our societies. Even if the awareness of soil importance is increasing, there is a need to further promote knowledge about soil functions and services not only among citizens but also among professionals, for example in areas such as urban planning (Teixeira da Silva et al. 2018). This issue still receives little consideration in politics and society (Dazzi and Lo Papa 2022).

DOI: 10.5281/zenodo.17430539

The specific questions associated with this gap are:

1. How do different actors perceive the relevance and need for the no net soil sealing and no net land take targets? What actors are likely to oppose the most, and why?
2. Which factors affect the level of societal acceptance of no net soil sealing policies and to which extent?
3. What are effective ways to strengthen acceptance of slowing soil sealing and accelerating unsealing among different societal actors?

Links between soil sealing and land take

Soil sealing, the covering of soil with impervious materials, is closely linked to land take, which refers to artificialisation processes tied to urban development and infrastructure construction. Land take involves artificial land uses for purposes like housing, industry, transport, and recreation. Soil sealing varies considerably within artificial land use categories. This complicates estimates based on land use data alone. In maps like Corine Land Cover and Urban Atlas, soil sealing values are used to classify residential classes with different densities (e.g., between 50% and 80% for the "discontinuous dense urban fabric" of the Urban Atlas).

Some studies highlight variability in soil sealing across contexts. For instance, in Italian cities, industrial areas showed soil sealing rates between 53.1% and 62.4%, while commercial zones ranged from 65.3% to 74.6% (Salata et al. 2019). A broader European study using Copernicus Imperviousness Density High-Resolution Layer data revealed soil sealing rates in the urban areas of 100 largest cities ranging from 31.5% to 72.6%, with a North-South gradient (Decoville and Feltgen 2023). These findings underscore the complexity of linking soil sealing with land take and the importance of detailed data to support policies aimed at sustainable land management. A clear understanding of the degree of soil sealing across different land use categories, land take processes, and its variability across contexts is essential to assess how achieving no net land take contributes to the no net soil sealing target, and vice versa. Without this understanding, the relationship between these objectives remains uncertain.

The specific questions associated with this gap are:

1. What is the degree of soil sealing associated with different land take processes? How does it vary in different contexts (e.g., for the same land use class across different countries)?
2. To what extent do the no net soil sealing and no net land take targets overlap?
3. What levels of soil sealing in urban areas allow for efficient land use and high density while also preserving ecosystem services with sufficient urban green spaces?

Overview

The initial list of knowledge gaps includes ten gaps presented in Table 2, along with four additional ones. These four additional knowledge gaps are:

1. Methods, indicators, and data to monitor soil sealing and land take;
2. Lack of consistent approaches for monitoring soil sealing/land take across Member States;
3. Quality of urban soils;
4. Social acceptance of soil reuse.

These additional gaps were assigned a lower priority during the first round of the prioritisation exercise and were therefore excluded from the main text.

The ten knowledge gaps in Table 2 are categorised into key and prioritised gaps, with a more detailed state-of-the-art analysis provided for the key gaps. Finally, the actions and associated bottlenecks related to all the gaps were identified, discussed within the Think Tank, and summarised in Suppl. material 1.

DOI: 10.5281/zenodo.17430539

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Endnotes

***1** In the context of the EEA monitoring, land consumption was defined as the sum of “all land use processes occurring on or ending up in developed land”, thus including both new land take as well as any other land use change involving artificial uses either as the initial or as the final use of the land.

DOI: 10.5281/zenodo.17430539

Soils for Europe

Outlook on the knowledge gaps to soil pollution and restoration

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Contributors and Reviewers

We would like to thank all the stakeholders of our Think Tank for their valuable contributions to this revised document, by providing very valuable written or verbal contributions, bilaterally, during organised events online or in person, or during the project meetings in Barcelona, Spain and Sofia, Bulgaria.

We would like to thank all the co-authors, readers and reviewers of the current and the previous versions of this document for taking the time to read the document and providing feedback. We highly appreciated all comments, critiques, suggestions to improve the document in this and former development and reviewing phases. All feedbacks had been, and will be, processed, considered and integrated in the current and the future development of the knowledge gaps assessment within the future course of the Soils for Europe project.

We would like to thank especially János Bogárdi, Shaswati Chowdhury, Monica Farfan, Violette Geissen, Caroline Heinzel, Karen Louise Johnson, Mellany Klompe, Guusje Koorneef, Anna Krzywoszynska, Gerry Lawson, Karen Naciph, Willem Ravensberg, Robin Simpson, Trine Sogn, Nicolaos Stathopoulos, Tibor Tóth, Felix Wäckers.

We would also like to thank all co-ordinators of the Soils for Europe project, and the Think Tank leaders of the other Think Tanks, for the valuable guidance, coordination and exchanges.

Abreviations

The abbreviations which are used in the text are listed in Table 1.

Table 1. Abbreviations.

Abbreviations	
AMR	Antimicrobial drug resistence
AMF	Arbuscular mycorrhizal fungi
AOM	Ammonia-oxidizing microorganisms
ARGs	Antibiotic resistance genes
CMEF	Common Monitoring and Evaluation Framework
CUPS	Commonly Used Pesticides
EC	European Commission
EEA	European Environmental Agency
EFSA	European Food and Safety Authority
EU	European Union
FAO	Food and Agriculture Organization of the United Nationas
GA	General Agreement of the SOLO project (official document)
GHG	Greenhouse Gas
ICM	Integrated Crop Management
IMPEL	European Union Network for the Implementation and Enforcement of Environmental Law
IPCHEM	Information Platform for Chemical Monitoring
IPM	Integrated Pest Management
JRC	Joint Research Centre
LUCAS	Land Use/Cover Area frame Survey
NGO	Non-Governmental Organizations
NOEC	No-Observed-Effect Concentration
OECD	Organisation for Economic Co-operation and Development
PAHs	Polycyclic Aromatic Hydrocarbons
PCBs	Polychlorniated biphenyls
PFAS	Per- and polyfluoroalkyl substances
POPs	Persistent Organic Pollutants
PRTT	Pollution and Restoration Think Tank
SML	Soil Monitoring Law (officially: Soil Monitoring and Resilience Directive)
SSDs	Species Sensitivity Distributions
SUD	Sustainable Use of Pesticides Directive
SUR	Sustainable Use of Pesticides Regulation
TCA	True Cost Accounting
UNEP	United Nations Environment Programme

1. Introduction

This paper is a summary of the preliminary results of the work of the Soil Pollution and Remediation Think Tank (PRTT) based on the previous scoping documents that underwent various reviews. PRTT was established as one of the 9 Think Tanks (TT) of the SOLO Soils for Europe project. The project's final aim is to deliver actionable transdisciplinary roadmaps for future soil-related research activities in the European Union (EU), which contribute to achieving the objectives of the Soil Mission. The task of the TTs including the PRTT's is to identify knowledge gaps and novel avenues for European soil research, innovation, and action in the context of the Soil Mission specific and operational objectives. The paper consists of three main sections.
The first chapter provides an introduction, including an overview of the overall scope of the PRTT and stakeholders' engagement. The second chapter introduces the conceptual framework developed for the review of the state of the art, knowledge gaps, actions and bottlenecks, and provides an assessment of the state of the art specific to pollution and remediation within the context of PRTT's scope. The third chapter provides the summary of the top 10 knowledge gaps identified during the prioritization process, along with their description, suggested actions and bottlenecks which may hamper needed actions, and need to be overcome.

The preliminary results reflect the intertwined nature of the knowledge gaps. During the further iterative process of the SOLO project, combining stakeholder engagement and literature review, each of the knowledge gaps, their prioritisation, actions and bottlenecks, will be further analysed in detail. The final deliverable will provide a roadmap with a final list of prioritised knowledge gaps, concrete actions for research and innovation, and associated bottlenecks. In the SOLO project context, two types of knowledge gaps are acknowledged: knowledge development gaps

DOI: 10.5281/zenodo.17430539

and knowledge application gap s. By definition, a '*knowledge development gap*' is a knowledge gap that requires generating new information or understanding by research or innovation, inclusive of both natural and social sciences and humanities' contributions. While, a '*knowledge application gap*' is a knowledge gap that requires research or innovation to find and/or test new mechanisms that allow the effective implementation of already existing information or understanding to improve soil health. This knowledge gap hence concentrates on the deficient links between available knowledge and its implementation and application. Regarding actions, by definition an '*action*' encompasses a spectrum of technical, social and economic strategies, approaches, measures, and/or solutions aimed at addressing identified knowledge gaps. These actions are aligned with the R&I priorities outlined in the Soil Mission framework. They serve as the means to achieve the research and innovation goals set forth by the Commission. In the SOLO roadmaps, each knowledge gap type can be addressed by both research and innovation actions. Finally, bottlenecks are barriers that hinder a successful implementation of suggested actions to solve both types of knowledge gaps. With the described content, the final roadmap shall support reaching the Soil Mission Objectives.

Soils, being largely hidden, have been overlooked, up until recently, by EU and national laws and policies, and given less importance than air, water and marine environments. However, the interconnectedness between air, water and soil, specially in terms of the transport of contaminants and pollution management has been recognised not only in the scientific literature but also in the Zero Pollution Action Plan (European Commission 2021a). Healthy soils can perform several functions and provide a wide variety of ecosystem services (supporting, regulating, provisioning and cultural Millennium Ecosystem Assessment 2005, EEA 2023a). They are essential to human health, to biodiversity, nutrient cycling, sustainable plant production, natural pest control, good water quality, water retention, carbon storage and erosion management (GIZ 2021). Soils are estimated to harbour 59% (Anthony et al. 2023) or up to more than 99.9% (Blakemore 2025) of Earth's species and possibly more. For example, at least 90% of fungi, 85% of plants and 50% of bacteria are living in soils (Anthony et al. 2023), and provide the basis for healthy ecosystems and human health (European Commission et al. 2020). Soil pollution is one of the main factors compromising soil functions (Rodríguez-Eugenio et al. 2018, FAO & ITPS 2015), thus soil health. Soil pollution has an impact on soil biodiversity, soil functions and ecosystem services and on human health and well-being.

Due to their strong linkages to environment, nature, biodiversity, ecosystem functioning, agriculture, human and animal health, and water and climate, soil pollution and restoration are relevant and connected to a wide framework of EU policies and legislations (European Commission 2023a, European Commission: European Environment, Joint Research Center et al. 2024). Specific EU legislation on soils has been lacking for many years. The Soil Strategy reviewed the state of soils back in 2004-2005. Now almost twenty years later, we are still facing similar problems/issues. As part of The European Green Deal and the Biodiversity Strategy for 2030 (Montanarella and Panagos 2021), an EU Soil Strategy for 2030 was published in 2021, setting out a framework and measures for the protection, restoration and sustainable use of EU Soils (European Commission et al. 2020, Panagos et al. 2022a). A linked policy process for the development of a draft of Soil Law was initiated, leading to the publication of the proposal for an 'EU Directive on Soil Monitoring and Resilience' ('Soil Monitoring Law', SML) by the European Commission (EC) on 5th of July 2023. At the time of writting, as a result of the trilogue negotiations (involving representatives of the European Parliament, the Council of the European Union and the EC) a provisional agreement was reached between the Parliament and the Council on April

DOI: 10.5281/zenodo.17430539

10, 2025. On June 4, 2025 the EU Parliament's Committee on the Environment, Public Health and Food Safety voted in favour of the agreed text and final voting on it by the Council and the Parliament is expected in early Autumn. Soil protection, regardless of the the lack of a separate EU legislation dedicated to soil prior to the publication of the SML proposal, has been, or is, part of different environmental legislations, and environmental relevant policies such as the Common Agricultural Policy. However, implementation issues relevant to soil pollution have been raised in reports of the European Union Network for the Implementation and Enforcement of Environmental Law (IMPEL 2010, IMPEL 2017) and in the reports of the European Court of Auditors (European Court of Auditors 2020a, European Court of Auditors 2020b), as well.

There have been several EU legislations and proposals that are directly related to the soil policy framework and mentioned as relevant in reaching the main goals. One of them was the proposal of the European Commission on a Sustainable Use of Plant Protection Products Regulation (SUR) (European Commission 2022b), which would have replaced the current Directive on Sustainable Use of Pesticides (SUD). The proposal aimed to reduce the use and risk of pesticides by 50% by 2030, (a goal of the Farm to Fork Strategy), and lead to the effective implementation of Integrated Pest Management (IPM). However, the proposal was rejected by the European Parliament in November 2023, and retracted by the European Commission in February 2024. Although IPM has been mandatory since 2014 under SUD, implementation in member states has been lacking, as well as implementation of other obligations of the SUD (European Court of Auditors 2020b, European Parliamentary Research Service 2018, European Commission 2020b). The outcome of the Strategic Dialogue on the Future of EU Agriculture highlights the importance of effective implementation of current evironmental and social legislation, the protection of soil health, and the reduction of inputs such as pesticides and fertilisers; in that framework the Commission is also expected to tackle the lack of implementation of the current SUD, including the lack of implementation of IPM.

The two main guiding documents setting the policy frameworks for soil and directly addressing soil pollution are:

1. the Implementation Plan of the Soil Mission, which is also an important component of the European Green Deal (European Commission 2021b) and:
2. EU Action Plan: 'Towards Zero Pollution for Air, Water and Soil' (European Commission 2021a). As part of the EU's zero pollution ambition, the Chemicals Strategy for Sustainability Towards a Toxic Free Environment was also developed (European Commission 2020a).

These policy documents specify the problem areas regarding soil health (polluting economic sectors/activities and polluting agents) and identify targets, based on assessments of the state of the art regarding soil health, identified needs and feasibility of reaching specific goals. One of the outcomes of the implementation of these elements is the SML proposal.

The aim of the SML proposal published is to be a cornerstone in reaching the objectives of the EU Soil Strategy for 2030 and the Soil Mission. The SML proposal is much needed and widely welcomed; however, it was also criticised by scientists, civil society and drinking water companies (Wageningen University 2023a, EEB 2023, EurEau 2023, Umwelt Bundesamt 2023) because it does not address all goals and targets identified in the policy documents. Therefore, improvements in the proposal and/or further legislative proposals are needed in order to reach healthy soils by 2050. The lack of clear rules and objectives, the lack of focus on soil biodiversity and diffuse pollution and the lack of linkages with water pollution and legislation, have been identified as essential shortcomings of the proposal by the scientific community (EEB 2023, EurEau 2023, Wageningen University 2023b, Pieper et al. 2023, Kotschik et al. 2024). Moreover, during the plenary vote in the European Parliament in April

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2024, essential provisions of the proposal were drastically watered down, further compromising the potential impact of the proposal (European Environmental Bureau 2024). The revised version of the SML waiting for adoption has incorporated new provisions to ovecome some of the concerns raised and it is an important step further.

The current PRTT used the problem areas described in these documents as a starting point to identify the state of the art and knowledge gaps, and to provide input for roadmap co-development. Roadmap co-development in this case means the involvement of stakeholders from various fields related to soil pollution and restoration toand jointly develop a roadmap towards programs which reveal the actions to be taken in prioritised manner. The PRTT will focus on soil pollution, soil restoration and remediation, while also taking into account the impact on, and of, soil pollution regarding connected systems such as crops and vegetation, water bodies (groundwater, surface water), air, (air or water borne pollution or pollution through leaching and volatilization processes) and overall ecosystem health and ecosystem functioning.

1.1. Scope (specific to PRTT)

The above two strategic documents, namely the Implementation Plan of the Soil Mission, and the EU Action Plan: 'Towards Zero Pollution for Air, Water and Soil' set specific targets related to limiting soil pollution.

As a basis, the PRTT aims to provide an analysis of the state of the art and an assessment of knowledge gaps, potential (innovative) solutions and actionable research regarding formulated goal's objectives, targets and indicators based on the two main policy documents. PRTT will address the complexity of the issues involved in soil pollution and reflect on their intertwined nature by highlighting the need for a holistic approach and integration of soil aspects to all relevant policies (the need for such an approach is well demonstrated by the Impact Assessment Report accompanying the SML (European Commission 2023c). It is important to identify policy areas that are directly linked to soil pollution, because the various policy instruments used in those fields do have an intentional or unintentional impacts on pollution that should not be ignored but explored through well-defined research questions.

Table 2. below indicates the concrete Targets, Baseline and Soil health indicators of the Soil Mission to be achieved by 2030 (European Commission 2021b, p. 16) and viewed as capable of contributing to meet the 2050 target: *Air, water and soil pollution is reduced to levels no longer considered harmful to health and natural ecosystems and that respect the boundaries our planet can cope with, thus creating a toxic-free environment* (European Commission 2021a, European Commission 2021b). It means, that e.g. based on the targets indicated in the table, the percentage of lands under organic farming has to be increased from 8.5% to 25% by 2030.

The listed targets and indicators of the Soil Mission do not address all pollution problems identified in the Support Material, nor those in the Zero Pollution Action Plan as it is demonstrated

Table 2. Targets and proposed soil health indicators for the mission objective: Reduce pollution and enhance restoration in the Soil Mission Implementation Plan. (Source: Soil Mission Implementation Plan, p 16).

Mission targets in line with EU and global commitment	Baseline	Soil health indicators
1: reduce the overall use and risk of chemical pesticides by 50% and the use of more hazardous pesticides by 50%	27% - 31% of land with excess nutrient pollution Soil contamination: 2.5% (non-agricultural), 21% (conventional arable), ca. 40-80% of land from atmospheric deposition depending on the pollutant.	Presence of soil pollutants, excess nutrients and salts
2 reduce fertilizer use by at least 20%		
3: reduce nutrient losses by at least 50%	Farmland under organic agriculture: 8.5% (2019)	
4: 25% of land under organic farming		
5: Reduce microplastics released to soils to meet 30% target of zero pollution action plan		
6: Halt and reduce secondary salinization		

DOI: 10.5281/zenodo.17430539

by the background working documents of the SML. While the targets, baselines and indicators are clear reflections of the intention to reduce pollution to a level that is no longer harmful to soil, health and natural ecosystems, there are some aspects that need further clarification to make the targets operational such as baseline year for calculating percentages. In some cases these negotiations have been already taking place outside of the Soil Mission (e.g. the reduction of the use of pesticides) which demonstrates the interlinkages and intertwined nature of the various policies.

1.2. Engagement within the PRTT

The science-policy-practice interface is a hot topic of scientific research (Miles et al. 2017) and especially relevant to environmental issues (Cvitanovic and Hobday 2018) within the context of the circular economy and sustainability (Kujala et al. 2023, Heikkinen et al. 2023). One of the primary benefits of stakeholder engagement (Kovács et al. 2021; Stankovics et al. 2024) is the creation of links between science and society, providing access to additional information or resources, and improving the relevance or utility of the research to users and beneficiaries. Concretely, through engagement, the project's results can be tailored to local contexts, increase the possibility that the outcomes are applied, and therefore, have a positive impact. Stakeholders engagement and the diversity of stakeholders' background and organisational affiliation promotes cross- fertilization of knowledge and innovation. (González-Piñero et al. 2021).

Identification of the stakeholders

Identification of relevant stakeholders has been, and still is, a process partly linked to the conceptual framework (Figure 3.). While the General Agreement of the SOLO project (GA) set the main categories (policymakers, civil society, practitioners, industry agents, scientists) of stakeholders to be approached, the conceptual framework served as an additional aspect of consideration. While using the snowball method (Durham et al. 2014), it was important to find examples for all of the stakeholder categories of the conceptual framework reflecting:

- on how the impact of pollution affects them (negatively or positively) and:
- on what kind of relationship they have with decision making (influencing and making/ taking decisions).

Agricultural and non-agricultural human activities, regional representation and decision making levels (EU, regional, national, local) were considered. PRTT's choices of stakeholders promotes the science-policy-practice interface by having stakeholders from science, policy and practice. The stakeholder involvement process resulted in a good representation both regarding geographic origin and professional background. Stakeholders can be grouped to various categories, based on professional and/or scientific background, organisational affiliation, sectors (agriculture, non- agriculture). The numbers of stakeholders change according to the categories applied (e.g. when organisational affiliation is not playing a role, the number of scientists is the highest as it is shown by comparing the data of Figure 1 a), b) and c)). Figure 1. d) on sectors is a good indication of the intertwined nature of sectors.

Most of our stakeholders fit into more than one of the categories. This helps to overcome the issues (e.g. hindrance of trust, causing conflicts) raised in relation to diversity of organisations in innovation projects reported in some studies (González-Piñero et al. 2021). The issues raised there are relevant to stakeholders and stakeholder engagement, as well. Successful collaboration with stakeholders is dependent on trust built between them and the engaging partner, and how conflicting views and interests of stakeholders are handled by the project partners. Miscommunication stemming from the diversity of stakeholders is often the source of misunderstanding and conflicts. Stakeholders fitting under more than one category could be instrumental in overcoming those issues, since they may understand and be familiar with the language and the position of the others.

Fig. 1 is a demonstration of it reflecting the stakeholders (in total 21) at the time of the preparation of the first version of the scoping document.

DOI: 10.5281/zenodo.17430539

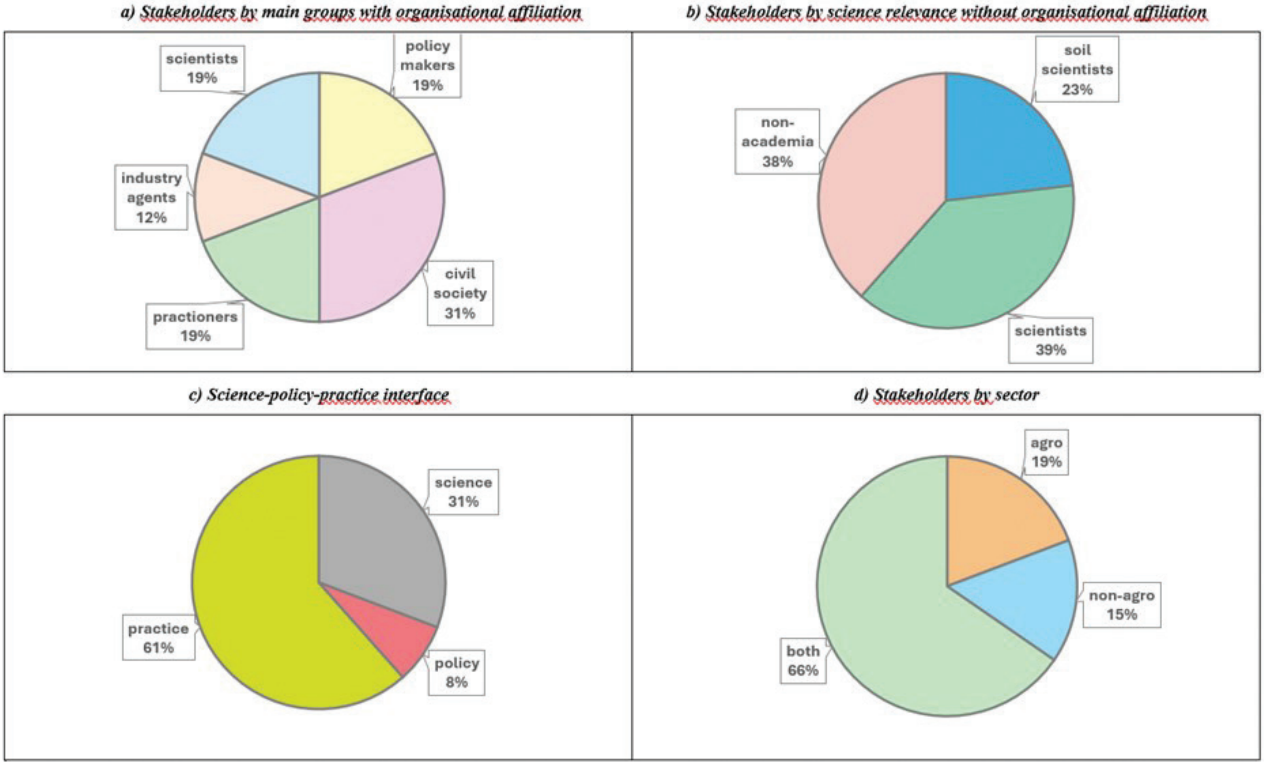

Figure 1. Introduction of stakeholders by different categories (created by the PRTT).

Figure 1. a) reflects on the GA categories and mainly organisational affiliation was applied to distinguish between the stakeholders:

- Policy maker: member of policy making bodies and public institutions with the task of preparing/developing/implementing/reviewing policy
- Civil society: non-governmental organizations (NGOs), giving voice to the citizens
- Practitioners: farmers, advisors without organisational affiliation
- Business: business organisations and business interest groups
- Scientists: Scientists (including PhD students) having affiliation to academic (education and/or research) institutions.

Figure 1. b) makes a distinction between scientists and non-academia stakeholders, breaking down the scientists category into two subcategories for making the number of soil scientists in the scientist group visible.

Figure 1. c) is to show the numbers of stakeholders relevant for the science-policy-practice interface:

- Science: all scientists irrespective of organisational affiliation
- Policy: non-scientists policy makers
- Practice: all non-scientists other than policy makers

Figure 1. d) is a reflection on the conceptual framework's (Figure 3.) categories on human activities (agriculture, non-agriculture). The category 'both' indicates that the stakeholder has interest in both sector relevant categories (e.g. health authorities, environmental NGOs).

Stakeholder engagement process

Stakeholders have been engaged from the very early stage of development of the scoping document. Most of the stakeholders werehad been individually approached and the project explained to them. Their reflections had influenced the first draft of the document, particularly the system-approach of Figure 3. The first draft of the scoping document was sent to all stakeholders, and based on their availability, they reflected on the content during semi-structured

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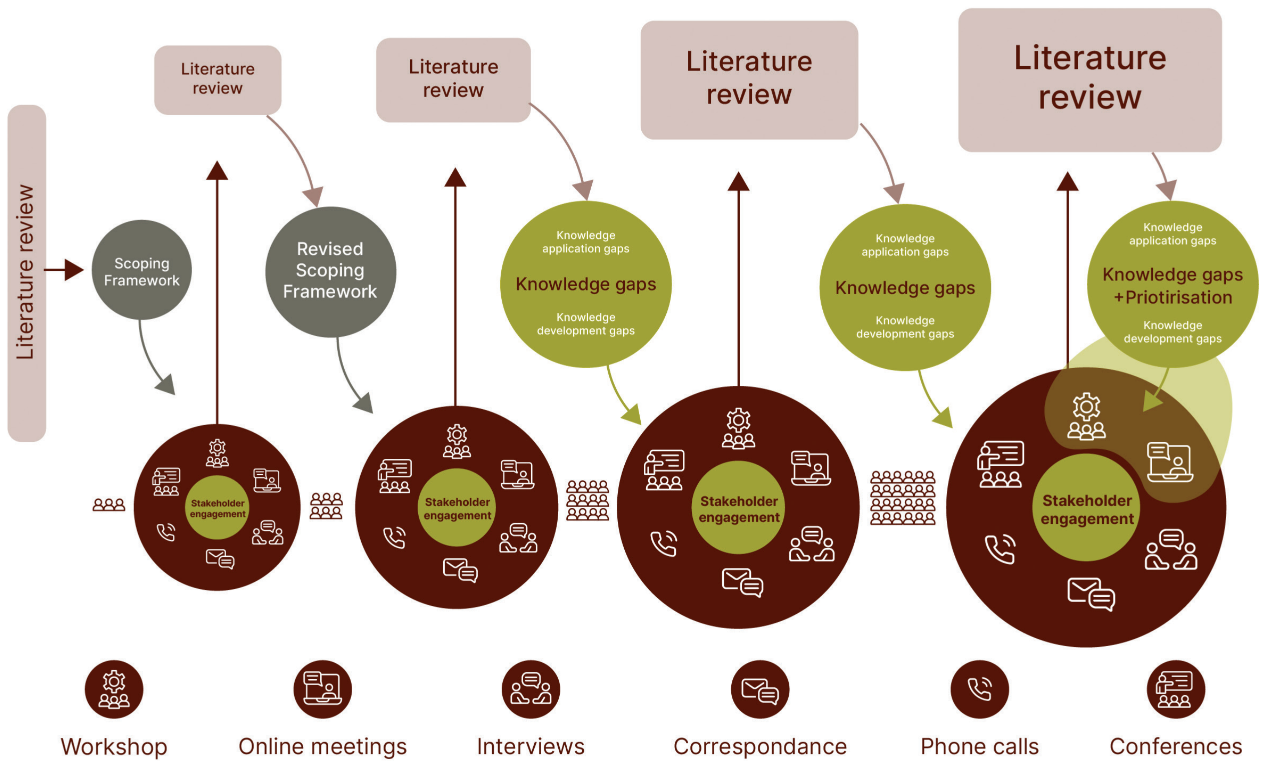

Figure 2. Visualisation of the methodology of developing a priority list of knowledge gaps: Iterative process and snowball effect approach of literature review, engagement with stakeholders (feedback, validation) and prioritisation. (created by the PRTT with PENSOFT).

interviews, or just shared their opinions in oral or written form. Stakeholders' comments were integrated into the current version. Figure 2. (Fig. 2) depicts this process based on the snowball effect relevant to both stakeholders chosen and literature reviewed.

Stakeholders expressed their views on the presentation of the content and also on the issues addressed in the document as a whole and particularly in the figures, and tables. Stakeholders' opinions were summarised based on the content of their feedback into two main categories: Format (F) (e.g.: transparency of the figures and tables), and Substance (S), the latter category being broken down into three subcategories depending on what action it required: to add (Sa), to complete (Sc), to improve understanding (Siu). The scoping document was modified after assessment and evaluation of the comments. All comments were relevant and useful. The format of the figure has been changed, and some of the suggestions were integrated into the document. However, not all of the comments were directly inserted, in some cases further elaboration of the topic was sufficient. The same approach was followed concerning this Revised document.

Table 3. summarises the comments on the first drafts of the scoping document and their acceptance by the main categories of the stakeholders.

Table 3. Stakeholder's reflections on the first draft (created by the PRTT).

Stakeholder by categories	Overall feedback	Categories of specific comments	Integrated into the document (X=yes, 0=no)
Scientist	positive	Sa, Siu	X
Practice	positive	F, Sc, Siu	X
Civil society	positive	Sa, Sc	X
Policy	positive	Sa, Sc, Siu	X
Business	positive	Sa, Sc,	X
...			

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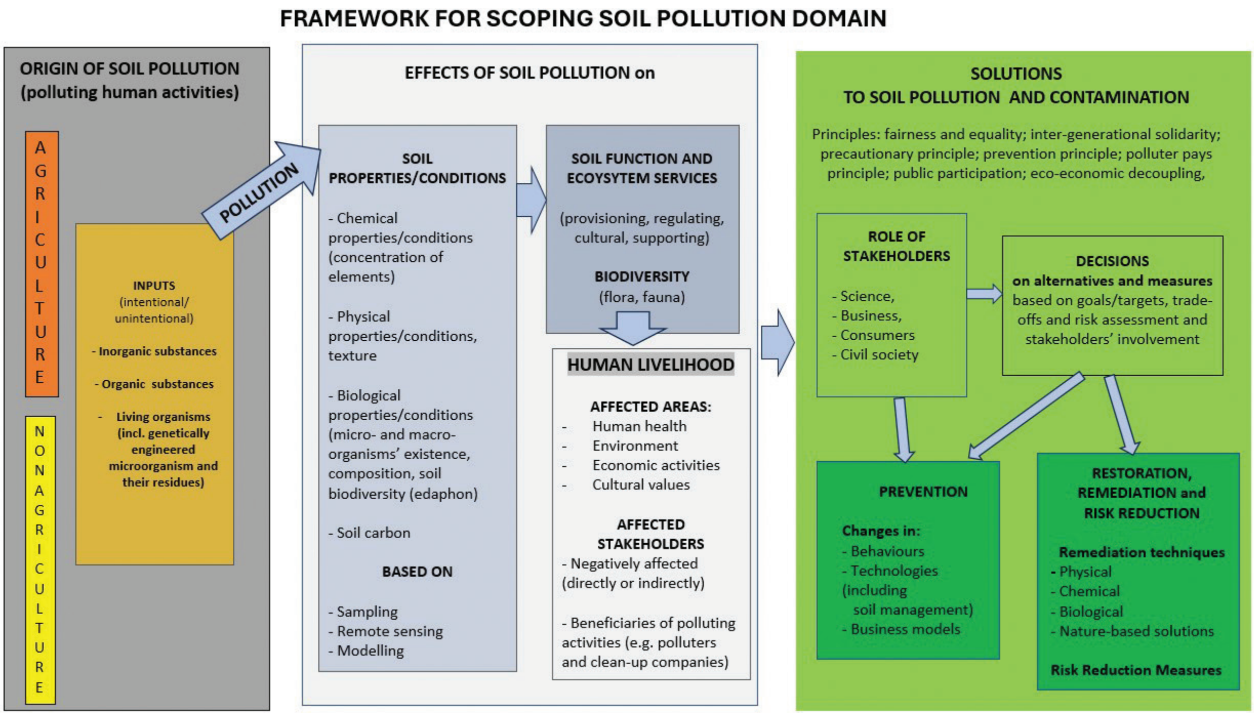

Figure 3. Refined concept overview of System approach to identify interlinkages between domains related to soil pollution/ contamination (created by the PRTT).

State of the Art

The state of the art in the soil pollution and restoration domain will be further reviewed during the next phases of the project. In this chapter, we lay down the principles and methods to develop a comprehensive overview of the domain, and provide a summary of relevant available knowledge, literature and stakeholders' views and experiences. It should be noted that the literature review was limited to literature available in English. Knowledge and knowledge gaps recognized and published in other languages than English could not be considered. However, taking the importance of site specificity and methodological diversity (relevant to pollution/contamination, pollutants/contaminants) into account it is of the utmost importance to gain insight of research results of the member states' scientific community, and the views of the stakeholders published and expressed in their native language.

Based on scientific evidence, soil-pollution-relevant documents of the EU, the Food and Agriculture Organization of the United Nations (FAO), the United Nations Environment Programme (UNEP) the Organisation for Economic Co-operation and Development (OECD), have emphasised the significant negative impact of soil pollution and land contamination on nature, its ecosystem services and human life. However, the use and the meaning of the terms 'pollution' and 'contamination' is not systematic in those documents and in the literature. The words 'pollution' and 'contamination' have different meanings but are often used as if they are interchangeable (Rodríguez-Eugenio et al. 2018). EU documents like the Zero Pollution action plan refer to the definition of the Directive 2010/75/EU, Article 3(2) (European Parliament and European Council 2010): *'Pollution means the direct or indirect introduction, as a result of human activity, of substances, vibrations, heat or noise into air, water or land which may be harmful to human health or the quality of the environment, result in damage to material property, or impair or interfere with amenities and other legitimate uses of the environment'.* While in the FAO document on soil pollution a different term is used: "*soil pollution: refers to the presence of a chemical or substance out of place and/or present at higher than normal concentration that has adverse effects on any non-targeted organism.*" (Rodríguez- Eugenio et al. 2018, FAO 2020)

DOI: 10.5281/zenodo.17430539

The difference between the two terms are important. The EU term is more anthropocentric. Concerning contamination, definitions on contaminant or contamination vary according to the topic or the approach of the document. While in the same EU directive (European Parliament and European Council 2010) the terms 'contamination', or 'contaminant', are not defined, and contamination is referred to only in the definition of the 'baseline' report, the SML proposal waiting for adoption provides for a broad definition of 'contaminant' by extending the scope of the term to a substance liable to cause contamination of both soil and bedrock or parent material. The FAO document on pollution uses the term 'contamination' with no reference to human activities, while the joint report of the FAO and UN on the world's natural resources defines contaminant by using the ISO definition (Rodríguez-Eugenio et al. 2018). While the differences can be justified, it makes comparative analysis difficult, especially when data mining tools are used.

Similar issues should be solved concerning the terms of ecosystem services due to the differences between the terms of the Millenium Ecosystem Assessment Report (Millennium Ecosystem Assessment 2005), the Intergovernmental Science-Policy Platform's reports (Rounsevell et al. 2018) and the EU's applied Common International Classification of Ecosystem Services (Haines-Young and Potschin 2018).

We identified the diversity of the definitions which makes harmonised review difficult. However, the elaboration of the issues based on the conceptual framework of the PRTT does not require harmonisation at this stage. During the next phase of the project the issues related to definitions will be addressed. For the time being, the terms are used as in the original sources.

2.1. Current state of the knowledge on soil pollution and restoration - System-approach and conceptual framework

A system-approach was developed to comprehensively tackle all aspects of the soil pollution and soil restoration/remediation domain by using the above-mentioned documents as a starting point, the literature review listed under Reference and the feedbacks from our stakeholders. The following studies provided more input for the development of the system-approach framework shown in Figure 3. (Fig. 3). Adhikari and Hartemink (2016), Babí Almenar et al. (2021), Bouma (2014), Greiner et al. (2017), Jónsson and Davíðsdóttir (2016), Lacalle et al. (2020), O'Riordan (2021), Pulleman et al. (2012), Stolte (2016), Vári et al. (2021), Velasquez and Lavelle (2019), Villa et al. (2014), Stavi et al. (2016), Dushkova et al. (2021), Wade (2022), JRC and Maes (2020), Ponge (2015), Wood and Blankinship (2022).

Putting soil health into the centre of the system-approach allows us to highlight all elements that are relevant for reaching the Soil Mission objectives of 2050, to demonstrate the complexity of pollution issues including the intertwined nature of policies and to provide a framework for assessing the state of the art, the knowledge gaps and to identify key research questions. A schematic overview of this system approach and the components of the system are presented in Figure 3. It is an updated version of the framework presented in the scoping document as a result of the iterative process (shown in Figure 2.) regarding the identification and fine-tuning of the knowledge gaps/actions/bottlenecks. Three main domains were identified as pollution relevant during the scoping process along with the principles that should be integrated into all domains, since they reflect on pollution relevant social and economic aspects. The development of the framework was driven by the Soil Mission Objectives relevant to PRTT which prioritise pollution from agricultural activities over other sources and sets specific targets for agriculture, compared to the general targets for other sources without making distinction between polluting human activities and/or sectors.

The three domains:

1. **Soil pollution:** identification and assessment of the extent of polluting agricultural and non-agricultural human activities,

DOI: 10.5281/zenodo.17430539

pollution originating from intentional or unintentional introduction of potential pollutants including (i) inorganic substances, (ii) organic), (iii) living organism (with characteristics of becoming biological pollutant) based on (i) soil descriptors and (ii) criteria reflecting on soil health.
2. **Effects of pollution:** identification and assessment of the extent of the impact of soil pollution on i) soil properties and conditions including linkages with other polluting pathways, ii) ecosystem services, soil functions and biodiversity and iii) human livelihoods reflecting on (a) the negatively affected (directly or indirectly), and (b) the beneficiaries of polluting activities (e.g. producers of polluting substances, polluters and clean-up companies).
3. **Solutions to soil pollution:** Identification of availability of and need for both solutions focused on *(i)* pollution prevention and *(ii)* restoration and remediation, as well as *(iii)* the assessment of the role of different stakeholders influencing decision making (scientists, business, civil society, consumers) and policy decisions/frameworks in view of (implementation of) solutions, *(iv)* decision makers. Individual stakeholders or groups of stakeholders can belong to one or more of mentioned categories.

The relevant principles for reaching soil pollution reduction targets (2030 and 2050) that should be integrated into all domains:

- **Fairness and equality:** distribution of and access to natural resources should be fair providing equal opportunity to everyone
- **Intergenerational justice:** refers to the close relationship between generations and mutual respect (Rockström et al. 2023)
- **Precautionary Principle:** allows measures to be taken to avoid risk of environmental harm, even in the face of scientific uncertainty
- **Prevention Principle:** allows preventive measures to prevent the occurrence of environmental damage
- **Polluter Pays Principle:** costs related to environmental damage should be borne by those who caused it
- **Public Participation:** the public is involved and is given early and effective opportunities to participate in all stages of the process elaborating preventive measures, when all options are still open
- **Eco-Economic Decoupling:** breaking the links between economic growth and environmental pressure.

2.2. Summary of the State of the Art on Soil Pollution and Restoration

This part provides a summary of the state of the art in the domain of soil pollution and restoration, based on relevant literature reviewed and inputs of stakeholders gathered so-far. The state of the art will be further developed during the next phases of the project. Specifically, it will be strenghtened with further reviews of key relevant grey and scientific literature, as well as with information and outcomes from relevant projects, and stakeholders' inputs.

2.2.1. Sources and scope of soil pollution

In this section, a first overview is given of important factors contributing to soil pollution. This overview will be extended and further elaborated during the following phases of the project. In section 2.2.2 and 2.2.3, a first summary of important impacts of soil pollution is provided. Two main types of soil pollution are mostly considered in literature: point-source soil pollution and diffuse soil pollution. However, based on the literature human induced soil pollutions can be categorised by

- **the source of pollution** (point-source soil pollution–diffuse soil pollution),
- **main sectors and drivers identified for pollution** (industry, agriculture, waste, mining, hazards, military activities and lately

DOI: 10.5281/zenodo.17430539

firefighting (European Commission: European Environment, Joint Research Center et al. 2024). Note, that the six drivers (technology and management, demography, policy and institutional arrangements, economy, nature and environment, socio-cultural context) identified by SOLO regarding four land uses (nature, urban, agriculture, forest) are relevant to all TTs (Chowdhury et al. 2024).

- **type of pollutants and their properties** having negative impact on soil properties, soil biodiversity, soil functions/ecosystem services and or human health,
- degradation pathways
- **the direction of transportation** via air and water (to of from soil),
- **decision making and the intention** (intentional/unintentional) of human activity related to input of potential pollutants.

In the literature reviewed, there is no separate category for decision-making, that reflects on decisions on aimed at reaching a balance between input and output of substances and where pollution is the result of an imbalance between input and output. In the case of agriculture, farmers continuously need to make decisions by taking into consideration all the aspects that may have an impact on the balance (crop choice, soil's properties, site specific conditions, timing, etc.), while iIn the case of non-agriculture activities, the balance is "established" during the development of the technology, thus the user of the technology does not have to, and is not allowed to, make any decision in this regard based on the technical descriptions of the product and/or safety procedures.

Concerning nutrient (nitrogen and phosphorus) soil pollution, it is important to emphasise that it is caused by the surplus (input minus crop uptake), while nutrient deficiencies (negative nitrogen and phosphorus) lead to nutrient mining affecting soil fertility and the capacity of soil production function (Rodríguez-Eugenio et al. 2018, Majumdar et al. 2016). European Commission: European Environment, Joint Research Center et al. (2024) Majumdar et al. 2016Rodríguez-Eugenio et al. (2018)

Relevant information on some of the above categories are summarized below.

The source of pollution:

• Point-source soil pollution

Point-source soil pollution is associated with sites where accidental or intentional spillage took place, and current or former industrial, waste disposal, mining, transport infrastructure and storage sites. Inorganic and organic pollutants, heavy metals, Persistent Organic Pollutants (POPs) and Polycyclic Aromatic Hydrocarbons (PAHs) are pollutants often involved in point-source soil pollution. The revised urban wastewater treatment directive underlines the negative impact of micropollutants and the need to monitor and to introduce quaternary treatment in order to remove micropollutants like pharmaceuticals and plastics (European Parliament and European Council 2024).

Point-source pollution also frequently involves historic contamination. Available data on the number and the area extent of contaminated sites in the EU are characterised by large knowledge gaps. The JRC estimated in 2018 that EU-28 counted about 2.8 million potentially polluted sites: sites where polluting activities are taking place or took place (Paya Perez and E.N. 2018). An EEA report published in 2022, based on national registries, showed that in 2016 1.38 million potentially contaminated sites were registered. About two- thirds of contaminated sites could be potentially historic (e.g. brownfields) (EEA 2022b). In 2016, 115,000 contaminated soils were estimated to be remediated in the EU; about 8.3% of the currently registered potentially contaminated sites. It is estimated that at least 166, 000 additional sites are in need for remediation or measures which reduce risk (EEA 2022b, European Commission 2023a). Historic contaminated sites don't fall under current legislation regarding industrial pollution prevention, such as for example the Industrial Emissions Directive (European Parliament and European Council 2010). The the SML proposal, waiting for adoption does include provisions on identification, assessment and management of contaminated sites, and aims to at least partly fill this policy gap. Also, data on remediation of contaminated sites are scarce/limited.

DOI: 10.5281/zenodo.17430539

- **Diffuse Soil Pollution**

Diffuse soil pollution involves soil pollution whereby substance is transported under a gradient of chemical potential, activity or concentration that often spreads over large areas, and in general doesn't originate from an easily identifiable, single source. These characteristics cause important challenges in assessing the full scope of diffuse soil pollution. Diffuse pollution often leads to chronic exposure to lower concentrations of pollutants, while the health and ecotoxicological impact of chronic exposure are difficult to assess, and have been less researched. Agro-chemicals, fertilizers and manure are important contributors to diffuse soil pollution, as well as road traffic and the diffusion of point-source pollution. Often, diffuse soil pollution is further transported by air and water. Important diffuse soil contaminants are listed below (Paya Perez and E.N. 2018, IUNG 2019, Rodríguez-Eugenio et al. 2018).

Selection of key pollutants and their properties:

- **Pesticides**

Agro-chemical soil pollution, including pesticides, has been identified as a major soil threat (Stolte 2016). Different studies (Chiaia-Hernandez et al. 2017, Hvězdová et al. 2018, Orton et al. 2013, Pose-Juan et al. 2015, Qu et al. 2016, Silva 2022, Silva et al. 2023, Franco et al. 2024) have already provided data on the distribution of currently approved or banned pesticides in soils. However, a comprehensive overview on pesticide residues in the soils in Europe through regular monitoring programs has been lacking, with existing data originating from different methods and analyte lists, and different sampling periods and strategies used among different studies, etc. (Institute of Environmental Sciences (CML), Leiden University and Royal HaskongingDHV 2024).

An important source of information on the presence of pesticide residues in European soils is the work of Silva et al. (Silva et al. 2019, Silva et al. 2022, Silva et al. 2023, Silva 2022, Franco et al. 2024). A pioneer, large-scale study analysed 76 pesticide residues in 317 EU agricultural topsoils showed that 83% of soils contained 1 or more residues, while 58% of soils contained mixtures of different pesticides (Silva et al. 2019). These findings were corroborated by a larger and more comprehensive study, conducted in the framework of the H2020 SPRINT project. A total of 209 pesticide residues were tested in 625 environmental samples in different matrices (soil, crop, outdoor air, indoor dust, surface water and sediment), across 10 study sites (Silva et al. 2023, Knuth et al. 2024). In 86% of the complete set of samples at least one residue was measured, and in 76% of samples mixtures of different pesticides residues were found. 201 of the samples were taken in soils, and revealed occurrence of 100 different pesticides. In soils of conventional farms, 99% of the samples contained pesticides, while 96% contained mixtures of at least two pesticide residues. For soils of organic farms, these numbers were 95% and 79% respectively.

The most frequently detected substances were p,p'dichlorodiphe-nyldichloroethylene (DDE p,p'), aminomethylphos-phonic acid (AMPA), a degradation product of glyphosate, hexachlor-obenzene (HCB), chlorpyrifos, and glyphosate. Total concentrations of pesticides in conventional fields reached a maximum value of 28.678 ug/kg, and 5.458 ug/kg in organic soils.

The study of Silva et al. (2019) made use of 317 samples from the 2015 LUCAS survey (Land Use/Cover Area frame Survey) (Orgiazzi et al. 2022, Franco et al. 2024). The 2018 LUCAS program included a pesticide module, which may be extended at least in terms of sample coverage in future LUCAS programs, in line with the SML.

Although still limited, the available data show that mixtures of pesticide residues are the rule rather than the exception, in soil and connected matrices. Large-scale, harmonized monitoring of mixtures of pesticides residues is urgently needed to evaluate risk for ecosystem and human health (Silva et al. 2023), accounting also for transport of residues in and on soil.

Limited data is available on the actual application of (individual) pesticides, which will change with the implementation of the Regulation on Statistics on agricultural inputs and outputs (European Commission 2022c). Pesticide sales data,

DOI: 10.5281/zenodo.17430539

a proxy for actual applications, show that pesticide use in the period 2011-2022 has remained relatively stable, hovering between 370 000 ton and 320 000 (Eurostat 2022b), with sales for some years, e.g. 2019 (333 000 tonnes) and 2022 (322 000 tonnes), decreasing, and for others, e.g. 2020 (346 000 tonnes) and 2021 (355 175 tonnes), increasing (Eurostat2025).

- **Persistent Organic Pollutants (POPs)**

Important sources of POPs are emissions from agriculture, combustion and industry, and from disposed commercial products (e.g. plastic containing POPs). The waste sector is relevant for the more recent POPs, for example through application of sludge. Data on POPs pollution of soils are very limited. For example, a EU study from 2011 (European Commission 2011) included only limited data on 4 POPs pollutants in soils. Under the Stockholm Convention, data on POPs for 2021 (UNEP 2021a) were gathered, however important data gaps remain. Long-term POPs pollution trends have shown no decline in Benzo(a)pyrene (B(a)p) air pollution and high concentrations of polychlorinated dioxines and furans (PCDD/Fs) in Europe (TF HTAP 2021).

Also, for emerging contaminants, such as the widely used Perfluoralkyl chemicals (PFASs), an important lack of data exists. PFASs resist degradation, and are easily transported over long distances. PFASs pollution is widespread, including in soils, water and waste. Remediation of sites polluted with PFASs is technically challenging and costly (Council of the European Union 2019).

- **Pharmaceuticals (including veterinary products) and personal care products**

An estimated 5,507.4 tonnes of active substance of antimicrobial Veterinary Medicinal Products were sold in Europe in 2020 (EU-27, UK, Iceland, Norway and Switzerland). In the period 2011-2020, a decrease of 43.2% was reported in sales of the 25 countries providing annual data to the European Medicines Agency (European Medicines Agency 2021). Through manure application, veterinary products end up in the soil (Gros et al. 2019), while pharmaceutical and personal care products can pollute soils through sewage sludge application (Gworek et al. 2021). No comprehensive data exist on the scale of contamination of these compounds in the EU. The continuous release of antibiotics into the environment is of important concern. The majority of antibiotics are not completely metabolised in humans and animals, and a high percentage is discharged into water and soil through animal manure, municipal wastewater, sewage sludge and biosolids (Perruchon et al. 2022). Antimicrobial drug resistance (AMR) poses an important challenge (Cycoń et al. 2019). Manure can also be a source of antibiotics from veterinary medicines (Antikainen et al. 2008, Panagos et al. 2022b).

- **Plastics and microplastics**

Plastic pollution, including microplastics and nanoplastic has emerged as a growing concern for soil health. Available data from Eurostat (Eurostat 2022a) indicate that the generation of plastic was increasing from 9.5 million tonnes in 2004 to 17.2 million tonnes in 2018. The fate of plastics once they enter terrestrial systems is poorly understood. Agricultural activities are a major source of soil plastic pollution, through the use of mulching (estimated rate of 100, 000 tonnes per year in the EU), application of sewage sludge (31, 000 to 42, 000 tonnes yearly) (Lofty et al. 2022), polymer-coated fertilizer and pesticides, plastic used in greenhouses, crop protection nets and irrigation systems (EIP AGRI 2020). In addition to direct agricultural use, microplastics reach soils through multiple diffuse sources, leading to the widespread presence of microplastics in the environment and in food. Degradation of macroplastics and cosmetics are sources, and also tyre wear is estimated to be an important source of microplastic pollution (Baensch-Baltruschat et al. 2021). Furthermore, plastics can enter soils through compost and organic amendments, industrial activities, landfill emissions, and mismanaged plastic waste. Even biodegradable plastics, such as starch-based or polylactide (PLA)- based films, are not exempt from contributing to soil pollution. Although marketed as environmentally friendly, these materials often fail to fully decompose under field conditions.

DOI: 10.5281/zenodo.17430539

They tend to fragment into smaller particles, adding to the pool of microplastics in soils (Meng et al. 2023, Briassoulis 2004, Whitacre 2014 de Souza Machado et al. 2018). The environmental behaviour of these so-called bio-microplastics is not well understood, and their long-term effects on soil ecosystems, including microbial activity, plant development, and pollutant transport, remain largely unknown. An important and under-explored pathway of soil contamination is the leaching of chemical additives from plastics (Macan et al. 2024). Plastics often contain phthalates, bisphenols and other additives, which may leach into soil and groundwater. In addition, other environmental pollutants (e.g. pesticides, heavy metals, POPs) can adsorb on the surface of microplastics, potentially enhancing their mobility and bioavailability in soils. This carrier effect represents a poorly understood risk to soil ecosystems. Despite growing evidence of widespread contamination, systematic data on the distribution, composition, and impacts of microplastics in European soils remain highly limited. There is also limited understanding of how microplastics affect key soil functions such as nutrient cycling, water retention, and soil biodiversity. Large-scale, harmonized assessments are urgently needed to better quantify the presence and risks of microplastics in soils, especially in the context of their interactions with other soil pollutants and their persistence over time.

- **Nutrients**

More than 70% of ecosystem area in the EU is at risk of eutrophication due to excess nitrogen deposition (EEA 2024). In the EU+UK, a worrying 74% of agricultural area receives excessive nitrogen inputs. Also, phosphorus has accumulated in agricultural soils in Europe, after the introduction of phosphorus-containing fertilizers in addition to manure. Large areas face surpluses of phosphorus. The primary cause is fertiliser and manure application, livestock density and soil degradation (erosion and leaching) in agriculture (European Commission: European Environment, Joint Research Center et al. 2024, European Environment Agency 2018, European Environment Agency 2019, Velthof et al. 2011).

This surplus of nitrogen in soil leads to an acceleration of microbial nitrification that further stimulates emissions of nitrous oxide, a highly potent greenhouse gas (GHG), and contamination of groundwater via nitrate leaching (Kuypers et al. 2018). Antikainen et al. 2008Panagos et al. 2022Majumdar et al. 2016European Commission: European Environment, Joint Research Center et al. 2024Rodríguez-Eugenio et al. 2018.

- **Heavy metals**

About 6.24% of EU agricultural area is estimated to contain high concentrations of heavy metals (concentration above the guideline value set by the Finnish legislation for contaminated soils in agricultural areas) (Ministry of the Environment, Finland 2007). Copper, lead and zinc are estimated to be accumulating in EU soils, while for cadmium a net decline is estimated (De Vries et al. 2022). High concentrations of copper are found in vineyards and orchards in humid climates, because of a high use of fungicides (Ballabio et al. 2018). Ballabio et al. (2021) found that EU hotspots of mercury are located close to mine areas, coal-fired power plants and chlor-alkali industries.

Concerning the assessment of soil heavy metal contamination and remediation needs Tóth et al. (2016) highlights that European countries have a number of approaches to define risk levels associated with different concentrations of heavy metal in soil (Carlon 2007, Ferguson 1999). It underlines that the Finnish standard values represent a good approximation of the mean values of different national systems in Europe (Carlon 2007) and India (Awasthi 2000) and they have been applied in an international context for agricultural soils as well (UNEP et al. 2013).

Beyond agricultural soils, data on heavy metals are limited. Panagos et al. (2021) estimated that the average concentration of mercury in EU topsoils amounted to 103g/ha. About 6 tonnes per year would be transferred downstream via transport of sediments (EU27 + UK). Tóth et al. (2016) indicated that heavy metal concentrations in soils are very unevenly distributed through the EU, with many sites of highly concentrated pollution.

DOI: 10.5281/zenodo.17430539

Pourret and Hursthouse (2019) have suggested to use the term 'Potentially Toxic Elements' instead of 'heavy metals' when reporting environmental research. During our further work within the PRTT, we will explore this option.

2.2.2. Impacts of soil pollution on biodiversity and ecosystems

Different studies have indicated important negative impacts of soil pollution on ecosystems and their services (water purification, water retention, food production, biodiversity, etc.) (Morgado et al. 2018, Rodríguez-Eugenio et al. 2018, Panneerselvam et al. 2022).

For example, pesticide residues in soil hold risk for biodiversity, ecosystems and their services, and get transported to/taken up by other matrices (water, air, indoor dust, food, microorganisms/microbiota, animals, humans). Many pesticide residues are persistent, bioaccumulative or toxic to non-target species (Silva et al. 2019, Silva et al. 2023.) Pesticide residues in soil are shown to negatively impact soil macroorganisms, microbiota and the microbiome (Gunstone et al. 2021, Beaumelle et al. 2023, Pelosi et al. 2021, Riedo et al. 2021, Walder et al. 2022, FAO et al. 2020). Pesticide pollution in soils can alter processes in the rhizosphere, impact plant growth and resistance against pests, alter the composition of soil microorganisms, and can lead to an increase of pathogens and decrease of beneficial organisms. Also, changes in nutrient composition in roots, leaves, grape juice and xylem sap have been observed after pesticide applications (Brühl and Zaller 2021, Klátyik et al. 2023, Mandl et al. 2018, Ruuskanen et al. 2023, Zaller et al. 2018, Zobiole et al. 2010). Negative effects on soil organisms also impact fauna dependent on soil organisms, e.g. farmland birds (Rigal et al. 2023).

The excess of fertilizer and manure cause extensive negative impacts on waterways and biodiversity. E.g. mycorrhizal fungi, essential for many soil functions and services, are negatively affected by excessive nutrients (Origiazzi 2016). The multifunctionality of soils, and the trade-offs between excess nutrients and other soil functions, are assessed by Vazquez et al. (2020).

Pharmaceuticals, such as antibiocs, can affect soil microorganisms, for example by changing their enzyme activity and ability to metabolize different carbon sources, and by altering the overall microbial biomass and relative abundance of different groups (Cycoń et al. 2019).

Microplastics can impact soil physico-chemical properties (e.g. increase bulk density, decrease porosity and water holding capacity), soil micro-organisms, macro-organisms, plant growth and can leach toxic chemicals (Lofty et al. 2022, Vasileiadis et al. 2018 Vaccari et al. 2022).

Although, negative (potential) impacts of different soil pollutants on biodiversity and ecosystem functioning have been shown by a variety of studies, the long-term impact of the cumulative effects of different soil pollutants or the interactive effects of these different groups of pollutants, being present concurrently in agricultural soils (i.e. plastics and pesticides), on the variety of different organisms exposed remains unknown. In general, there is a lack of long-term studies that also evaluate the impact of mixtures and cumulative effects on a wide range of organisms and ecosystem services.

2.2.3. Impacts of soil pollution on stakeholders

Different studies have indicated that soil pollution directly affects human health. Soil pollution can contaminate food, which can pose risks for human health. Many links have been described between increased risks for a variety of illnesses and health impacts, and pollutants frequently found in soils, such as arsenic, lead, and cadmium, organic chemicals such as polychlorinated biphenyls (PCBs), PAHs, pharmaceuticals such as antibiotics, pesticides and micro-plastics (Rodríguez-Eugenio et al. 2018, Cox et al. 2019, European Commission 2019, Lim 2021). Rodríguez-Eugenio et al. (2018) underline the potential risks of contaminated soil for human health, including uptake from dust and vapours by farm workers, skin contact and ingestion of soil. Also, soil pollution/ contamination can be responsible in many cases for vector-borne diseases such as dengue, chikungunya, Zika, malaria, that are

DOI: 10.5281/zenodo.17430539

growing human health risk of the local population getting infected and transmitting the infection exponentially. (Krystosik et al. 2020, FAO et al. 2020, George et al. 2024).

Tolerable daily intake values for pesticide residues are likely to underestimate the risk to consumers, as they don't account for mixture effects. Pathways other than ingestion or food, such as inhalation or skin contact, are seriously underestimated. Soil pollutants, such as pesticide residues, can accumulate in the lighter top layer of the soil, and get transported by the wind and inhaled by animals and humans. Pesticide residues have also been shown to accumulate in indoor dust (Navarro et al. 2023). A recent paper by Matsuzaki et al. (2023a) highlights the potential links between pesticide exposure and the microbiota-gut-brain axis.

Overall, there is an important lack of research on the impacts of mixtures of soil pollutants people are exposed to, including on impacts on humans from long-term exposure to soil pollutants. Here the "exposome" is relevant: the measure of all the exposures of an individual throughout a lifetime and how those exposures relate to health. There is also an important link between the impact of soil pollutants on (soil) biodiversity and human health, as soil pollutants can lead to the selection for harmful taxa and to an overall decrease in diversity of microbiota, also leading to effects on the human microbiome. More and more research also refers to the impacts of soil pollutants on the gut microbiome, and potential links with health conditions, including neurological illnesses. Soil pollutants can lead to advantages for harmful microbiota, for example through antibiotics resistance (Roslund et al. 2024).

Soil pollution is associated with important economic and social impacts and costs. For example, soil pollution can negatively impact health, land availability, water quality, water retention, crop growth/food production and other ecosystem services (Adhikari and Hartemink 2016, Bouma 2014, Greiner et al. 2017, Jónsson and Davíðsdóttir 2016, JRC and Maes 2020, Lacalle et al. 2020, O'Riordan 2021, Pulleman et al. 2012, Stavi et al. 2016, Stolte 2016, Velasquez and Lavelle 2019).

2.2.4. Solutions to soil pollution

Solutions to soil pollution include prevention of pollution and remediation/restoration of contaminated sites. Prevention of soil pollution (due to intentional inputs of potential pollutants or unintentional inputs of pollutants) is a must in order to reach the Soil Mission Objectives. It is important to underline, that on the one hand, routine handling and use of chemicals in industrial activities often result in negative impact on soil and/or groundwater. This may occur when certain chemicals – earlier believed less harmful – prove to be hazardous to human health or the environment. This has happened earlier with certain chlorinated hydrocarbon compounds or with PFAS/PFOS compounds more recently. On the other hand, pollution due to unintentional inputs of pollutants are most commonly caused by chemical accidents. Since 1992 the OECD has published three guides on preventive measures relevant to accidents. Acknowledging the chance of accidents, the OECD developed its guideline Prevent-Preparedness-Response around three phase before, during and after accidents (OECD 2023b). FAO publications also addresses the prevention and risk management issues of agriculture induced soil pollutions (Drechsel et al. 2023), or the hidden costs that includes economic, environmental and social costs linked to the agrifood system (FAO 2023, FAO 2024a).

Prevention of soil pollution is a cycle of processes that consists of different, but interlinked phases:

- acceptance or refusal of a new substance (including potential biological pollutants) and/or process, technology for use,
- setting the rules for application (including but not limited to legislation),
- application (including the monitoring and surveillance of applications, enforcement of laws, and preparedness to accidents) and adaptation to the site specific conditions,
- adjustment if negative impacts occur (including changes in using/applying substances/processes/technologies, and emergency response in case of accidents),
- remediation to prevent further pollution (including follow up to incidents).

DOI: 10.5281/zenodo.17430539

Below, there are we present examples inof agricultur ale and non-agricultural soil pollution situations showing on how the phases of prevention and remediation/ restoration are interlinked.

Agriculture

Different practices and management tools are available to decrease soil pollution. IPM, Integrated Crop Management (ICM) and agro-ecological practices have been shown to provide effective approaches to minimizing inputs of pesticides and fertilizers, and maximizing ecosystem functioning and services, such as biological pest control. These approaches are based on increasing the resilience of the crop, while agro- chemicals such as pesticides are only used as a last resort, if needed, instead of prophylactic or calendar-based practices (Rodríguez-Eugenio et al. 2018, IPM Works 2022). Different EU legislations and initiatives are in force or in development which can contribute to reduction of soil pollution originating from agricultural activities.

Non-agricultural soil pollution

Remediation techniques are often divided into in situ (on the site) and ex situ (off the site) remediation, and include physical, chemical and biological treatments. Physicochemical treatments are often characterized with high speed and efficiency, but also with high costs and labour, and potential destruction of soil functionality. The field of remediation techniques has developed over time to a focus on effective restoration of soil quality and preservation of the environment, while minimizing the damage caused by clean-up interventions. Recent developments have also reflected the aim to promote clean-up strategies which also address climate change effects (Grifoni et al. 2022). Several in-situ chemical treatment technologies are emerging, including In-Situ Chemical Oxidation (ISCO) and In-Situ Chemical Reduction (ISCR) methods. Biological treatments provide eco-friendly features and larger social acceptance, but often require long periods. A wide variety of biological techniques have been developed and successfully applied. Microbiological methods aim to utilize the decay processes, when selected microbes utilize the pollutants for their growth, finally resulting in the elimination of the pollutants. These methods are widely used in practice.

Lacalle et al. (2020) provide an overview of biological methods of polluted soil remediation for an effective economically-optimal recovery of soil health and ecosystem services. Methods include phytoremediation, phytoextraction, phytostabiliziation, phytomanagement, bioremediation and vermiremediation. Specific challenges are associated with soils contaminated with multiple pollutants. The interaction between organic and inorganic pollutants can change bioaccessibility and solubility of pollutants and their biotoxicity and metabolic processes. For pollutants that are relatively new to the environment, such as PFAS, important challenges remain due to unknown pathways of degradation. Also, competition or joint-adsorption on binding sites poses a challenge. For mixed contaminated soils, successful combinations of chemical and biological remediation techniques have been discussed, although more research is needed (Aparicio et al. 2022, Lacalle et al. 2020). More research is needed on the potential of nature-based solutions and the use of microorganisms for bioremediation processes. In general, more research is needed to improve efficiency, feasibility, costs and time- efficiency of remediation techniques for a variety of different contaminants and soil conditions. As mentioned in the documents, those are significant knowledge gaps (Aparicio et al. 2022, Grifoni et al. 2022, Huysegoms and Cappuyns 2017, Lacalle et al. 2020, Ministry of the Environment, Finland 2007, Mulligan et al. 2001, Smith 2010). Different EU legislations and initiatives are in force or in development which can contribute to reduction of soil pollution originating from industry, traffic and waste.

DOI: 10.5281/zenodo.17430539

2.2.5. Social and economic tools to prevent soil pollution and their fitness- for-purpose

Important reoccurring aspects regarding socio-economic and market tools relevant to tackling soil pollution are the need for implementation of the polluter pays principle, as well as for the targeted use of public funds. Current legislation and funding does not always secure linkages between funding and protection of the environment and enhancement of ecosystem services (OECD 2023a). The polluter pays principle is insufficiently included in legislation, while the loss of ecosystem services associated with soil degradation is not integrated into economic optimisation of economic actors. Stakeholders underlined that several questions should be raised, such as: *Is it possible to devise fiscal or other financial measures to mitigate pollution in a way that spreads the cost of mitigation in an equitable fashion thus diminishing political opposition? To what extent is it possible to add self-regulation to the range of regulatory mechanisms? What is the price structure of the food chain downstream from the farm gate to the final consumer, and how it may affect the use of the polluter pays principle? How to tackle long-term effects of pollution and how to make the polluter accountable for it? How to deal with pollutants crossing borders? How could and should different legislations be applied? Is there an alternative to public funding of historic pollution where the polluter no longer exists?* The answer to the question 'Who should cover remediation costs of historic pollution?' remains often a challenge (European Commission 2023a). An important potential instruments is a pollution levy, e.g. a pesticide levy, which is used in Denmark (Nielsen et al. 2023). Austria has a well-designed tax on landfill, incineration and other forms of waste disposal: the waste disposal tax (Altlastenbeitrag) (European Commission 2021c). The questions raise the general question on 'What principle/principles should be applied?'. All principles mentioned in the conceptual framework should be considered during the review of the tools. The application of the precautionary principle is utmost important in preventing soil pollution and its negative impact.

2.3. Prioritization of knowledge gaps

In the initial phase of the project, the PRTT carried out a first appraisal of knowledge gaps regarding soil pollution and restoration, based on an assessment of available knowledge gaps' reviews, findings of former relevant projects, a review of a selection of key grey and scientific literature and exchanges with stakeholders involved. The preliminary knowledge gaps identified in that first phase were divided into four groups:

1. Definitions, scope, sources and loads of soil pollution,
2. Affected soil properties, ecosystem services and impacts on livelihoods,
3. Affected/Involved stakeholders and their role,
4. Solutions to soil pollution and needed conditions.

Fig. 4 summarised these initially identified knowlede gaps, in their respective groups.

The knowledge gaps identified during the first phase show that the first two groups of knowledge gaps in Figure 4. fall mainly within the first two domains (soil pollution and effects of pollution) of the conceptual framework (Figure 3.), while the second two address the issues of the second and third domains (effects of pollution, solutions to pollution) of the framework.

The previously identified knowledge gaps were reviewed, and reformulated through an iterative process with stakeholders described above. During the prioritization process, which included voting on knowledge gaps by stakeholders involved in the different SOLO TTs during 1) an in person meeting in Sofia, Bulgaria on 5-6 November 2024, and 2) an online meeting on 27th November 2024, the knowledge gaps below in Table 4. were identified as the top ten knowledge gaps. Each knowledge gap was

DOI: 10.5281/zenodo.17430539

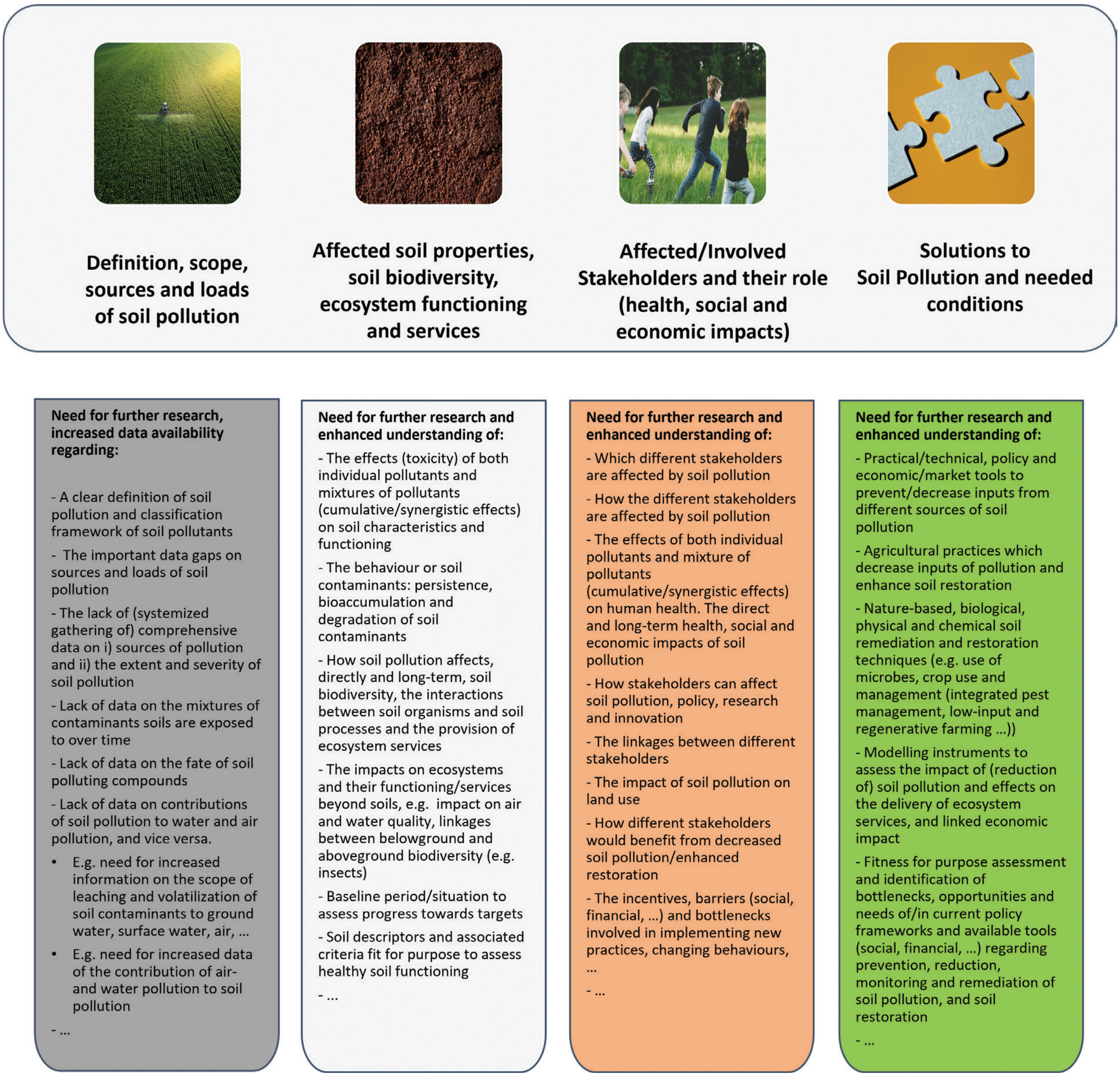

Figure 4. Overview of preliminary identified knowledge gaps regarding soil pollution and restoration (created by the PRTT).

identified either as a 'knowledge development gap' and/or a 'knowledge application gap'.

3. Roadmap for PRTT

This chapter provides a review of the knowledge gaps. It starts with the top 10 knowledge gaps identified in the rank order indicated in Table 4. Compared to the discussion of the three key knowledge gaps under 3.1., the other top seven knowledge gaps' discussion under 3.2. is shorter in length (as required by the template provided to each TTs by the project's leadership) and thus in depth. The rank order of the knowledge gap (within the top 10) is indicated by the number in the brackets. All introductions of the knowledge gaps include: 1. a summary, and information on 2. the state of the art, on 3. actions and on 4. bottlenecks. Section 3.3. provides the list of the knowledge gaps currently identified. For the top ten knowledge gaps the information includes: 1. ranking, 2. title, 3. shortened summary, 4. type of the knowledge gaps, 5. actions, 6. type of actions, 7. timeframe for actions, 8. bottlenecks. For the knowledge gaps outside of the top 10 knowledge gaps only the title and a short description is given. The number in the 'ranking' column does not reflect priority.

DOI: 10.5281/zenodo.17430539

Table 4. Ranking of the top 10 knowledge gaps identiefied (a full list of all identified knowledge gaps is given in section 3.3).

Rank	Knowledge gap	Type of knowledge g	ap
1	Impact of soil pollutants (individual and mixtures, short-term and long-term) on soils and soil ecosystem services	Knowledge developmen Knowledge application	t gap and gap
2	Socio-economic and market tools to prevent soil pollution and their fitness-for- purpose	Knowledge developmen Knowledge application	t gap and gap
3	Impact of soil pollutants (individual and mixtures, short-term and long-term) on human health	Knowledge developmen Knowledge application	t gap and gap
4	Data gaps on soil pollution and lack of systemized monitoring and methodologies	Knowledge developmen Knowledge application	t gap and gap
5	Technical/practical tools to remediate soil pollution and restore soils	Knowledge developmen Knowledge application	t gap and gap
6	Behaviour/transportation and fate of soil pollutants and link of soil pollution with water and air	Knowledge developmen Knowledge application	t gap and gap
7	Baseline, indicators/descriptors and quality thresholds/criteria	Knowledge developmen Knowledge application	t gap and gap
8	Overall impact of soil pollution on wider ecosystem functioning (beyond soils)	Knowledge developmen Knowledge application	t gap and gap
9	Technical/practical tools to prevent agricultural soil pollution	Knowledge developmen Knowledge application	t gap and gap
10	Knowledge gaps regarding the implementation and upscaling of preventative measures to address agricultural soil pollution	Knowledge application	gap

Table 5. Links between the knowledge gaps (as currently definied) and the conceptual framework's domains. 1. *Soil Pollution*: SPo: origin of soil pollution, SPi: input (properties of polluting agent); 2. *Effects of Pollution*: EPpc: Effect on soil properties/conditions, EPfesb: Effect on soil functions and ecosystem services, biodiversity, EPhul: Effect on human livelihood; 3. *Solutions to soil pollution*: SSPdec: decision for action (prevention/remediation), SSPprin: principles of the conceptual framework, SSPprev: prevention against polluting event or process, SSPrest: restoration/remediation, risk reduction.

Rank Knowledge Gaps	Soil Pollution	Effects of Soil Pollution	Solutions to Soil Pollution
1. Impact of soil pollutants (individual and mixtures, short- term and long- term) on soils and soil ecosystem services	SPo SPi	EPpc EPfesb	SSPdec SSPprev
2. Socio-economic and market tools to prevent soil pollution and their fitness-for- purpose	SPo SPi	EPhul	SSPprin SSPdec SSPprev SSPrest
3. Impact of soil pollutants (individual and mixtures, short- term and long- term) on human health	SPo SPi	EPpc EPfesb EPhul	SSPdec SSPprin
4. Data gaps on soil pollution and lack of systemized monitoring	SPo SPi	EPpc EPfesb EPhul	SSPprev
5. Technical/practical tools to remediate soil pollution and restore soils	SPo SPi	EPpc EPfesb EPhul	SSPrest SSPdec
6. Behaviour/transportation and fate of soil pollutants and link of soil pollution with water and air	SPo SPi	EPpc EPfesb EPhul	SSPdec SSPprev SSPrest
7. Baseline, indicators/descriptors and quality thresholds/criteria	SPo SPi	EPpc	SSpdec
8. Overall impact of soil pollution on wider ecosystem functioning (beyond soils)	SPo SPi	EPpc EPfesb	SSPdec
9. Technical/practical tools to prevent agricultural soil pollution	SPo SPi		SSPdec
10. Knowledge gaps regarding the implementation and upscaling of preventative measures to address agricultural soil pollution		EPhul	SSPdec SSPprev

The introduction of the top 10 knowledge gaps does not cover all three domains of the conceptual framework. The focus reflects the main issues elaborated in the referenced literature. Table 5. below links the knowledge gaps to the conceptual framework's domains. It is important to note that the indication of a domain does not mean that all aspects of it are discussed under the given knowledge gap.

As it is shown by the Table 5., the knowledge gaps are not yet linked to all domains of the Conceptual Framework. This exercise will be completed in the next phase. Table 5. in its present form serves as a guideline towards the future work of the PRTT. PRTT's aim is aim to provide an optimal level of generalization of the issues relevant to all domains of the conceptual framework, and to the Soil Mission Objectives.

DOI: 10.5281/zenodo.17430539

3.1. Key knowledge gaps

Under this heading the top three knowledge gaps which received the most votes during the prioritisation process are introduced.

3.1.1. Impact of soil pollutants (individual and mixtures, short-term and long- term) on soils and soil ecosystem services

Summary of the Knowledge Gap (Knowledge Gap 1)

The impacts of soil pollution are far-reaching and multifaceted, and pose significant challenges to environmental sustainability, public health and socio-economic well-being. Significant knowledge gaps exist concerning the impact of soil pollutants on soil characteristics, including on soil properties, soil biodiversity, soil functioning, aboveground organisms and the delivery of ecosystem services. For the majority of pollutants, there are no comprehensive (eco)toxicity data, and hence risk assessments, available (e.g. pesticides, volatiles, antibiotics, microplastics). Large data gaps remain on i) cocktail/mixtures and ii) cumulative and synergistic effects, while mixtures of soil pollutants in soils reflect the factual status. Large data gap exists on cocktail/mixture/ cumulative/synergistic effects, including a general lack of knowledge on individual substances (presence and interactions in soil, transport and fate, mobility and persistence, ecotoxicological properties, bioaccumulation and bioavailability, exposure of and risk to the environment).

State of the Art

The impacts of soil pollution are far-reaching and multifaceted, and pose significant challenges to environmental sustainability, public health and socio-economic well-being (De Vries et al. 2022European Commission: European Environment, Joint Research Center et al. 2024). Soil pollution is a main factor of decline in soil biodiversity (Tibbett et al. 2020 Gardi et al. 2013).

When data on toxicity and risk are available, they often focus on one pollutant and source, and are limited to a small set of test organisms, usually single species that are easy to breed, during a short time frame, focusing on a single toxic endpoint, in controlled (laboratory) conditions.

Cocktails of pollutants in soil include both co-occurrences of different pollutants within the same group of chemicals (e.g. different pesticides) and, as the co-occurrence of pollutants from different chemical groups (e.g pesticides and plastics). It is essential that the impact of long-term effects of mixtures of pollutants in field conditions is taken into account, to assess the probable impacts of soil pollution on long-term soil health and ecosystem functioning. Although available research clearly shows the extensive impacts and risks of soil pollution on soil characteristics, biodiversity and the delivery of ecosystem services, large data gaps still remain. The high complexity of soil and interactions of soil compounds, organisms and contaminants provides a large challenge in assessing the full impact of soil pollution on the delivery of ecosystem services (Rodríguez-Eugenio et al. 2018, Vieira et al. 2024).

The knowledge gaps regarding the impact of soil pollution on soil biodiversity and soil ecosystem services are multifactorial. 1) To date, the full scope of soil pollutants remains unknown, with only a selection of pollutants being measured, and harmonised monitoring data lacking. 2) Also, for the pollutants for which more data are available, comprehensive risk assessment is mostly lacking, as risk assessment mostly focuses on single pollutants and their short-term impact on single organisms, as described above. 3) Although available research shows the presence of complex mixtures of soil pollutants mostly everywhere, the impact of the combined effects of these mixtures is largely unknown. For a number of decades, it has been recognized that an integrative approach focused on complex mixtures of pollutants is needed to increase understanding of their full extent and potential impacts (Reeves et al. 2001, Albert 1987). Available research shows the extensive negative impact of soil pollution on biodiversity and ecosystem services. Some first steps have been taken to work towards more integrative approaches to assess

DOI: 10.5281/zenodo.17430539

the full impact of soil pollution on soil biodiversity and ecosystem services, and a more integrative assessment of soil pollutants. The SML includes calls for chemical and biological indicators as soil descriptors, for the assessment of soil health. Andres et al. 2022 suggested an indicator for in-soil organisms, and used ecotoxicological data, chemical occurrence and habitats for the indication of risks. However, available knowledge is still very limited, and extensive knowledge gaps remain. Based on review of literature and exchange with stakeholders, the following main groups of pollutants are addressed under this knowledge gap: pesticides, plastics, veterinary medicines, metals, excess of nutrients, pesticides and emerging contaminants/forever chemicals, with references to common features and differences. During the further work within the PRTT, the range of contaminants discussed might be further expanded.

All mentioned pollutants are major soil contaminants. They are either intentionally (pesticides, nutrients) or unintentionally (metals, veterinary medicines, plastics) released in soils where they impose adverse effects on non-target organisms. Amongst them, soil macro-organisms, mesofauna and microbiota constitute a key protection goal considering their contribution in key ecosystem services as they modulate soil fertility and soil structure, produce and store GHG, and degrade organic pollutants (Fierer 2017). The impact of soil pollution also reaches much further than soils, and leads to contamination of the wider, aboveground ecosystems, air and water bodies (groundwater, drinking water, freshwater and marine water) (Albaseer et al. 2025, Vieira et al. 2023). Despite the common features, all of them have their own characteristics.

Pesticides

Use of pesticides is widespread, and diffuse pollution by agro-chemicals has become a major soil threat (Stolte 2016, Silva et al. 2019; FAO et al. 2020, Vieira et al. 2023). Sabzevari and Hofman (2022) reviewed the worldwide occurrence of Commonly Used Pesticides (CUPs) in agricultural soils. Franco et al. (2024) identified risks for in-soil organisms on an European scale.

Complementary, Silva et al. (2023) highlighted the presence of pesticide residues across European environments, underscoring the need for better public data accessibility to track and eventually also regulate such pollutants. Nowadays, multiple efforts are made to create such datasets which will hopefully help us in the future (e.g. IPCHEM, NORMAN). In general, current risk assessment does not capture cumulative, combined and chronic exposure to pesticides, and resulting impacts on soil biodiversity, overall biodiversity and ecosystem functioning (Honert et al. 2025, Devos et al. 2022, Bopp et al. 2019, Sousa et al. 2022, EEA 2023b, van Gestel et al. 2020, Knillmann and Liess 2021). Risk assessment and research also focus mostly on the impact of single active substance or pesticide products, while large data gaps remain on the impact of tank mixtures (when different pesticide products are mixed and applied together) and environmental mixtures (the presence of different pesticide residues and other pollutants in the environment). More research is available on the toxicity and impact of active substances of pesticides, than on the impact of pesticides products (active substance, co-formulants and adjuvants), while pesticide products are often more toxic than the active substances (Mesnage and Antoniou 2018, SAPEA 2018). Thresholds for a few pesticide residues, metabolites have been part of the legislation of a few European countries (Carlon 2007), but mostly for currently banned and highly persistent pesticides (e.g. DDTs, HCHs, Atrazine). Furthermore, the lack of data on pesticide mixtures in soils, as well as data on the total load of diffuse contamination in soils, have prevented validation and improvement of current risk EU assessment of active substances, degradation of products and pesticides. The latter is currently based on prediction of environmental concentrations, based on recommended application rates. Only a few species of animals are used in EU pesticide risk assessment. Research has pointed to the lack of field data and lack of information on mixture and cumulative effects on soil organisms, including non-standard and native species and communities, soil functioning and ecosystem services (Geissen et al. 2021).

DOI: 10.5281/zenodo.17430539

As mentioned earlier, Silva et al. (2019) found that 80% and 58% of 317 soil samples across the EU contained respectively pesticides and mixtures of pesticides, with in total 166 different pesticide combinations. Silva et al. (2023) also measured pesticides in 201 soil samples in the framework of the H 2020 Sprint Project. They found 100 different pesticides, with the large majority (79%-99%) of samples containing mixtures of pesticides. Soils under organic farming mostly contained persistent, long-banned pesticides, while soils under conventional farming contained also recently banned and currently approved pesticides. The researchers conclude that non-approved compounds represent a significant part of the cocktails found, and should be accounted for in risk assessment. They also recommend re-evaluation of pesticides persistence. They point out that European Food and Safety Authority (EFSA) risk assessment currently focuses on single active substances, standard ecotoxicological tests and modeling exercise, with a few standard organisms, endpoints and conditions.

Research shows that pesticide contamination extends to landscape level, far beyond farmland. E.g. Brühl et al. (2024) found widespread contamination of soils and vegetation with pesticides and Silva et al. (2023) found widespread contamination of soils, air, water, sediments and indoor dust. Also in nature reserves, insect communities are not safe from pesticide exposure (Brühl et al. 2021). Brühl and Zaller (2019) pointed out as well that long-term and cumulative effects of pesticide mixtures are not considered in the current risk assessment of EFSA. They highlight as well that indirect food web effects of pesticides are not considered: e.g. the reduction of flowers and hence of food sources of bees is not included in current risk assessment. In 2024, EFSA received two mandates from the EC to review the outdated risk assessment for plant protection products. An outline for the revision of the terrestrial ecotoxicology guidance document and for the development of an approach on indirect effects has been already published (EFSA 2025).

Honert et al. (2025) underline that current pesticide use is recognised as the largest deliberate input of bioactive substances into terrestrial ecosystems, and one of the main factors responsible for the current decline in insects in agricultural areas. Analysing 93 active substances in monthly soil and vegetation samples over a year, a total of 71 active substances were found, with up to 28 in single soil samples. The concentration in the topsoil remained almost constant year-round, and peaked in vegetation in summer. The authors call this particularly worrying, as adult insects are mainly active (in vegetation) in summer, and adult insects or larvae living in the soil are chronically exposed to several pesticides. They point out that the constant presence of pesticide mixtures is not part of the regulatory environmental risk assessment procedures for pesticide regulation. Mixtures are addressed only occasionally in formulated products with up to 4 active substances. Therefore, authorities are urged to ensure that chronic contamination of complex pesticide mixtures is incorporated in authorisation procedures and risk assessment. Additionally, given that large-scale contamination is expected throughout the year, and only a fraction of used active substances is analysed, the calculated risks are supposed to be even higher. The authors conclude that only reductions in pesticide risk can change the current observed declines in insects, and that even with refinements of, for example focusing on regulatory adjustments, a comprehensive EU strategy must be adopted to decrease overall pesticide use and transition toward ecological farming methods. (Brühl and Zaller 2019, Honert et al. 2025, Mauser et al. 2025).

The adverse effects of pesticides on beneficial soil fungi and earthworms and other soil macro- and microbiota were described by several authors (Pelosi et al. 2021, Riedo et al. 2021, Klátyik et al. 2023). Wan et al. (2025) reviewed 1705 studies, concluding that pesticides cause negative responses of growth, reproduction, behaviour and other physiological biomarkers for non-target plants, animals (invertebrates and vertebrates) and microorganisms (bacteria and fungi). Similar to other experts, the authors underline the need for better risk assessment, as risk assessment currently focuses on a limited number of easily cultured model species, and are therefore unlikely to capture the variety of responses to pesticide exposure seen across the diversity of

DOI: 10.5281/zenodo.17430539

species and communities found in both managed and natural systems. Therefore, there is a need of cross-taxa synthesis of pesticide effects, and for integrating long-term low-level exposure, cumulative effects at the landscape level and synergistic interactions between active ingredients. The authors suggest that post-licensing biodiversity monitoring could help address this problem, and conclude that unless changes occur, the hazard of severe, unexpected and long-term impacts on biodiversity and ecosystem functioning will remain unacceptably high (Wan et al. 2025). Kotschik et al. (2024) and Pieper et al. (2023) also claimed for the feedback from monitoring results in regulation of chemicals.

Gandara et al. (2024) screened more than 1000 agrochemicals in a fruit fly model and found that the majority had behavioural effects at sublethal levels and even more compromised survival after acute exposure. When combining agrochemicals at field- realistic levels, the researchers found widespread changes to larval development, behaviour and reproduction.

Beaumelle et al. (2023) reviewed available data on the impact of pesticides on soil invertebrate communities, looking at abundance, biomass, richness and diversity of natural soil fauna communities across a wide range of environmental contexts. Their review shows that pesticides overall decreased the abundance and diversity of soil fauna communities, with more outspoken effects on diversity than on abundance. Scenarios with multiple substances, insecticides and broad-spectrum substances showed most detrimental effects. There was no evidence found that the effects of pesticides dampen over time: long-term and short-term studies showed similar effect sizes. The study found that pesticide use erodes a substantial part of global biodiversity, having significant detrimental non-target effects on soil biodiversity, and threatening the health of ecosystems. Gunstone et al. (2021) reviewed nearly 400 studies on effects of pesticides on non-target invertebrates which have egg, larval or immature development in the soil. The reviewed studies included unique species, taxa or combined taxa and different pesticide active ingredients or unique mixtures of active ingredients. Of the 2800 tested parameters, with each parameter representing a change in a specific endpoint after exposure of a specific organism to a specific pesticide, 70.5% of tested parameters showed negative effects, while 1.4% showed positive effects and 28.1% showed no significant effects. The authors conclude that all types of pesticides pose clear hazard to soil invertebrates, with evident effects for all studied classes of pesticides, in a wide variety of soil organisms and endpoints, and in both laboratory and field studies.

Franco et al. (2024) performed an evaluation of the ecological risk of pesticide residues from the European LUCAS Soil Monitoring 2018 survey, which assessed 118 pesticide residues in more than 3773 soil sites across whole Europe. The study presents two mixture indicators for soil based on the lowest and median of available No Observed Effect Concentration (NOEC) from publicly available toxicity datasets, to respond to the policy need to develop risk-based indicators for pesticides in the environment. The mixture risk indicator based on the NOECsoil,min which is currently used in the ERA of ppp exceeds 1 in 14% of the sites and 0.1 in 23%. The exceedance of 1, indicates a high risk for in-soil organisms due to analysed mixtures in soil samples. Across the 73 sites monitored in LUCAS 2015 and LUCAS 2018 both campaigns, the risk indicator increased slightly.

Undesirable effects on soil microbiota can now be well-documented using advanced and standardized molecular tools (Karpouzas et al. 2014a, Karpouzas et al. 2014b; Vasileiadis et al. 2018 Vischetti et al. 2020). However, at regulatory level obsolete low- resolution methods like the OECD 216 N transformation test are still in place to evaluate toxicity of pesticides on the soil microbiota (Karpouzas et al. 2022; Pedrinho et al. 2024).

Ammonia-oxidizing microorganisms (AOM), modulating nitrification in nitrogen cycling, and arbuscular mycorrhizal fungi (AMF), obligate symbionts of most terrestrial plants, have been identified as potent bioindicators to assess the toxicity of pesticides on the soil microbiota (Karpouzas et al. 2016, Ockleford et al. 2017). New methods like amplicon sequencing in combination with tools like Species Sensitivity Distributions (SSDs) could be used to quantify effects of pesticides, although standardization of these approaches is still missing.

DOI: 10.5281/zenodo.17430539

Shortcomings in risk assessment are also underlined by PAN Europe 2024, who highlights that the tests within the EU guidance document on 'non-target' arthropods are very limited and insensitive, allowing the mortality of as much as 50% of the population with the spraying of a single pesticide. They call for the need for independent (from business interest), transparent, science-based guidance documents to allow for the effective protection of the environment, including non-target arthropods.

Drift of pesticides, for example through run-off, the transport of pesticide residue attached to soil particles and volatilization from soils, is also described by many researchers as a danger to biodiversity (Albaseer et al. 2025). Drifting pesticides, find the authors, have profound impact on biodiversity, harming non-target plants, insects, fungi and other organisms both near application sites and in distant ecosystems. Pesticide drift has been linked to over 50% reductions in diversity of wild plants, within 500 m of fields.

Plastics are emerging and persistent contaminants whose relevance for soils was highlighted relatively recently (Nizetto et al. 2016). Weathering of plastics gives birth to micro-plastics (< 5 mm) which could impose adverse effects on the soil fauna (Huerta Lwanga et al. 2016, Quigley et al. 2024), affect soil structure and porosity and eventually impose undesirable effects on the soil microbiota (de Souza Machado et al. 2018). This could be assigned to additives that could diffuse from plastics in the soil matrix and have direct toxic effects on the soil microbiota (Zhu et al. 2022). Beyond that, the surface of plastic fragments constitutes a unique micro-niche for microbial colonization (called plastisphere) where other organic pollutants could adsorb and directly interact making plastisphere an arena of microbial interactions and rapid evolution (Rillig et al. 2024, Puglisi et al. 2019). The outcome of these interactions is only now starting to unravel with first evidence suggesting that plastics act as vectors of human pathogens and ARGs (Zhu et al. 2022), while their interactions with the other organic pollutants affect their dissipation (Lamprou et al. 2025). Recent evidence suggests that the co-occurrence of multiple stressors in soils could magnify the negative effects on the soil microbiota (Rillig et al. 2023), and that this aspect should be clearly considered in future studies. Further evidence also highlights potential detrimental effects on soil fauna and their associated gut microbiomes (Boughattas et al. 2024).

Another barrier in, especially, microplastic research is the fact that there are no standardized methodologies for the detection, quantification, and characterization of microplastics. This barrier makes it very difficult to compare different studies. Secondly, there is also a scarcity of long-term data on the fate, degradation, and potential accumulation of microplastics in soil ecosystems, particularly concerning their interactions with soil organisms and effects on ecosystem services. Microplastic transport through leaching represents another challenge. Finally, a difficulty that is often overlooked is that addressing the impact of microplastic pollution in soils requires collaboration across disciplines. This includes soil science, polymer chemistry and toxicology. However, limited interdisciplinary communication and data sharing can hamper comprehensive research efforts.

Veterinary medicines such as antibiotics and anthelmintics, end up in soil either directly through faeces deposition of grazing animals (grasslands) or manuring of agricultural soils (Fernández et al. 2011, Fang et al. 2023). Navrátilová et al. 2021Udikovic-Kolic et al. 2014 Besides that, the presence of antibiotics and anthelmintics in soils have been associated with strong adverse effects on the soil microbiota and particularly on AOM (Lagos et al. 2023, Lagos and Karpouzas 2023) and AMF (Gkimprixi et al. 2023) with reciprocal effects on soil fertility and plant productivity.

Despite extensive gaps remaining, **metals** are among the pollutants for which already more information is available regarding their effects on biodiversity. For example, metals and metalloids can impact microbial communities in soil, and impact different processes, such as carbon storage and cycling (Azarbad et al. 2015, Vieira et al. 2024). Faggioli et al. (2019), showed that Pb contamination can decrease abundance and richness of arbuscular mycorrhizal fungal communities. Important is also that the use of fertilizers can introduce heavy metals and other soil pollutants (Mantovi et al. 2003). Tőzsér et al. (2019) found that ground beetles can indicate extreme soil metal pollution.

Excess nutrients have an important impact on soil, water bodies, biodiversity and overall

DOI: 10.5281/zenodo.17430539

ecosystem functioning. Particularly nitrogen and phosphorus can transport to surface water bodies and groundwater, leading to eutrophication, loss of biodiversity, and oxygen-depleted waters (Lundin and Nilsson 2021). E.g. mycorrhizal fungi, essential for many soil functions and services, are negatively affected by excessive nutrients (Origiazzi 2016). Excess nitrogen also contributes to air pollution, with deposition of nitrogen one of the main driver of loss in plant biodiversity (Bobbink et al. 2010). Moreover, excess nitrogen in soil can cause increased emission of N_2O, an important GHG. (McDonald et al. 2021, Pan et al. 2022).

More than 70% of ecosystem area in the EU is at risk of eutrophiciation due to excess nitrogen deposition (EEA 2024). In the EU+UK, a worrying 74% of agricultural area receives excessive nitrogen inputs. Large areas also face surpluses of phosphorus. The primary cause is fertiliser and manure application, livestock density and soil degradation (erosion and leaching) in agriculture (European Commission: European Environment, Joint Research Center et al. 2024, European Environment Agency 2018, European Environment Agency 2019, Velthof et al. 2011).

This surplus of nitrogen in soil leads to an acceleration of microbial nitrification that further stimulates emissions of nitrous oxide, a highly potent greenhouse gas (GHG), and contamination of groundwater via nitrate leaching (Kuypers et al. 2018). Also, phosphorus has accumulated in agricultural soils in Europe, after the introduction of phosphorus-containing fertilizers in addition to manure. Manure can also be a source of antibiotics from veterinary medicines (Antikainen et al. 2008, Panagos et al. 2022b). Since the 1950s, the increased use of fertilisers has increased crop production. In India total grain production in 1995 was reached by 57 % more fertilizers than used in 1950 (Majumdar et al. 2016). However, their excessive and inefficient use has led to nutrient excesses and losses. The same has been experienced in the EU (European Commission: European Environment, Joint Research Center et al. 2024). The negative long-term effects on soil, water, biodiversity and human health have been ignored for a long-time. It has been argued that excess use of nitrogen may even have a countereffect on yield due to its negative impact on soil properties, soil life (Rodríguez-Eugenio et al. 2018) resulting in lower income to farm.

Emerging contaminants and ‘forever-chemicals’

Specific knowledge gaps are related to the lack of knowledge on the presence and therefore also of the effects of emerging contaminants on soil biodiversity and ecosystem services. Also, PFAS or ‘forever-chemicals’ are important soil pollutants, and characterized by specific concerns, due to their highly persistent nature, widespread use and toxicity at low concentrations (Brunn 2023, European Commission: European Environment, Joint Research Center et al. 2024). Ultrashort-chain PFAS such as Trifluoroacetic acid (TFA), irreversibly accumulating in different matrices across the EU, are described by researchers as a global threat, due to their important environmental and health concerns (Arp et al. 2024).

Impact on Soil Ecosystems and Functions, and Modelling

Soil pollution leads to impairments in ecosystem structure and functions (carbon transformations, nutrient cycling, maintenance of the structure and regulation of biological populations). Mining, agriculture, forestry and waste disposal jeopardize the functional biodiversity compartment of the ecosystem, which will also lead to destruction of the provision of goods and ecosystem services (Morgado et al. 2018).

Although some studies have carried out economical assessments of e.g. the impact of agriculture on the environment (Kurth et al. 2019), the environmental externalities of soil pollution have not been fully assessed across Europe. Likewise, benefits of decreasing soil pollution and positive impacts of restoring soil health on biodiversity and ecosystem services, including long-term, sustainable production of food, have not been comprehensively included in current evaluation assessments, including in existing models. For example, models assessing the impact of reducing pesticides often

DOI: 10.5281/zenodo.17430539

do not consider the medium- and long-term positive impacts regarding crop production which would result from soil restoration and enhancement of ecosystem services, such as increased pollination, natural pest control and protection against erosion.

The impact of soil pollution reaches far beyond soil ecosystems. The **interlinkages of soil pollution with air and water pollution** on the one hand, and **the impact of soil pollution on wider ecosystems, beyond soils** on the other hand, are also among the 10 identified priority knowledge gaps, which are further discussed.

Actions

- Ambitiously enhance systematic monitoring of soil pollution, to fill in the extensive gaps on presence of pollutants in soils,
- Include in environmental risk-assessment long-term, low-level, chronic, cocktail/ mixtures and cumulative/synergistic effects, feedback monitoring results in the authorisation of chemicals, as well as the indirect impacts, and impacts on landscape-level and ecosystem functioning/services, to integratively assess the impact on soil biodiversity and ecosystem services,
- Include all relevant studies in risk assessment, and ensure transparency,
- Research/action on prevention and remediation of soil pollution, e.g. transitioning to ecological farming methods and investing in nature-based solutions,
- Include impact of soil pollution on ecosystem functioning/services in modelling to support policy making decisions.
- Enhanced research on individual substances (presence and interactions in soil, transport and fate, mobility and persistence, ecotoxicological properties, bioaccumulation and bioavailability, exposure of and risk to the environment).

Bottlenecks

- The high complexity of soil and interactions of soil compounds, organisms and contaminants hinders the assessment of the full impact of soil pollution on the delivery of ecosystem services.
- Lack of systemized monitoring, and limited capacity leads to data gaps which hinder the determination of the level and spatial extent of pollutants in EU soils, both for point-source and diffuse pollution.
- Various and varying attitudes and, perceptions of actors involved in soil pollution hinder directing and attributing needed means and efforts to the identification and the assessment of the impact of soil pollutants and the extent of soil pollution.

3.1.2. Socio-economic and market tools to prevent soil pollution and their fitness-for-purpose

Summary of the Knowledge Gap (Knowledge Gap 2)

While the relationship between prevention of soil pollution and socioeconomic issues is two-fold, there is lack of a comprehensive framework and corresponding tools to tackle it. There is a need for developing tools that are capable of addressing and reflecting both sides of the coin and can simultaneously take into account their specific socioeconomic issues, and conflicting nature. There is no framework that addresses, on the one hand, the question of which socioeconomic changes and market tools can prevent soil pollution, and, on the other hand, how prevention of soil pollution changes those socioeconomic issues, while considering temporal and spatial context. In the first case, the focus is on the polluter and the polluting activity. In the second case, those who are exposed to soil pollution and its consequences are the focal point. In both cases, it is essential to have a clear understanding of the relationship between the socioeconomic status of the population and the impact of soil pollution/ prevention on that status. There is a need for an analytical framework for the review of the underpinning factors of the negative impacts of pollution and prevention, addressing what levers can be activated for turning around those impacts, what kind of new tools have to be developed, and

DOI: 10.5281/zenodo.17430539

how existing tools could be applied and/or adapted to reach the EU's goals related to soil health.

State of the Art

Socio-economic and market tools reflect the European social and economic model. As stated in the report of the working group "social and economic model", the European model is depicted by principles (solidarity and cohesion) and common values (freedom, equality, social justice, dialogue, respect for human rights based on equality among member states) that determine the model's characteristics and lay down the bases for sustainable development. While the European economy is a market economy, the principles of the model require that "*economic growth must serve to boost overall social wellbeing, and not take place at the expense of any section of society, especially young people*" (EC working group 2007). The adjective "socioeconomic" used in various terms describing status, development, growth etc. is always a reflection of the European model and should be interpreted in that context.

A large number of scientific papers exist acknowledging, describing and elaborating on the negative impacts of soil pollution on soil health, soils functions/ecosystem services and human health and addressing socio-economic impacts, and market tools, market failures and the need to change the regulatory framework. They are reflected in policy papers and reports (FAO 2015, FAO 2018, FAO 2020, FAO 2024b, UNEP and FAO 2021, UNEP et al. 2013, European Environment Agency et al. 2024, European Environment Agency 2019, European Environment Agency 2018, EEA 2022a, EEA 2022b, EEA 2023a, EEA 2019) OECD publications could become guidelines in assessing and developing tools and in evaluating their fitness-for-purpose (OECD 2008, OECD 2012, OECD 2020, OECD 2021, OECD 2023a, OECD 2023b, OECD 2024).

The structure and the logic of those papers can fit into the DPSIR model widely used by the EEA for analysing environmental issues (Stanners et al. 2007). Many of them assess the state of soil (S), identify pressures (P), and impact (I) and look for drivers (D), before calling for policy changes (Response – R). Based on this model, a complex response needs to be developed addressing all elements of the DPSIR model in order to mitigate or cease pressures resulting in a decreased or even zero negative impact.

As part of the SOLO project, drivers relevant to soil mission objectives were summarized. (Chowdhury et al. 2024) In the study, six categories of drivers were identified: 1. technology and management, 2. demography, 3. policy and institutional arrangements, 4. economy, 5. nature and environment, 6. socio-cultural context regarding four land uses (nature, urban, agriculture, forest). For all categories, the relevance of the drivers was assessed, identifying whether they are relevant everywhere, within the EU, or within a specific region or member state. Out of the 451 studies, 82 were related to soil pollution (agriculture 52, nature 16, urban 11, forest 3). There are significant differences in the data on soil pollution drivers for the different land use categories, the ranking corresponding to the number of studies. The site specificity of soil health and soil pollution issues could be underestimated since more than half of the agriculture and nature drivers' relevance was indicated at member state level only. Another review study on drivers identified four main groups related to human activities (1. industry and mining, 2. urban areas and transport, 3. agriculture, 4. hazards and military activities) as the main sources of pollution. It pointed out, that the reviewed studies adhered different importance to pollutants based on land use (Vieira et al. 2024). In 2002 the EC published a Communication (European Commission 2002) on the impact assessment to improve policy quality and coherence by simultaneously giving consideration to economic, social and environmental issues. The EC gave examples of impacts which should be reviewed during the impact assessment process. The *economic impacts* included macro- and micro-economic impacts relevant to economic growth, competitiveness, compliance costs (including implementation costs for public authorities), innovation and technological development, investments, market shares, trends in consumer prices. *Social impact* examples referred to various human rights, employment, health and safety issues, consumer rights, social capital, se-

DOI: 10.5281/zenodo.17430539

curity, education, training and culture and their distributional effects on income at different levels (sector, groups, workers, consumers). Examples of *environmental impacts* linked the negative and positive impacts to changes in the status of the environment manifested in climate change, air, water and soil pollution, land-use change, biodiversity loss, and decrease in public health (European Commission 2002).

The need to assess and evaluate socioeconomic factors and impacts of projects, and to foster socioeconomic development, have been key issues for decades. In 2002, the socioeconomic tools for sustainability impact assessment were summarized (Tamborra 2002). The Summary's aim was to provide tools for assessing the economic, social and environmental impacts of a regulatory approach in order to promote sustainable development. The main two objectives were the integration of economic and ecological dimensions by developing integrated models and finding ways to show the value of health and environmental damage in monetary terms, thus assessing those external costs of human activities. Socio-economic survey tools (Liswanti et al. 2012) could become important source of information on the socio-economic status of stakeholders and their interest in prevention of soil pollution and remediation. The integration of the various aspects is challenging especially regarding agriculture, where the diversity of the natural, environmental, historical, social, cultural, economic factors among the member states is significant (Andrejovská and Glova 2022). While Darnhofer et al. (2010) argue that resilience thinking can integrate ecological, economic and social aspects into farming systems, D'Adamo et al. (2020) emphasise the challenges in taking all three into consideration when developing the new socio-economic indicator for bioeconomy sectors. They underline that the lack of relevant environmental data was the reason why the environmental aspects could only be integrated in the future. It would be important to review whether the new socioeconomic indicator could be used and further developed to tackle the issues regarding prevention of soil pollution and/or remedation.

The need to assess the socioeconomic impact has been part of the earlier and recent Horizon project calls, and evaluation (EC DG R&I 2017, European Commission 2018). The calls refer to different socioeconomic aspects, however, they do not necessarily specify which factors, nor which status, to consider.

In 2018 the EC published a document (European Commission 2018) to help the assessment of socio-economic and environmental impacts of Europe's R&D program. The guide refers to the use of the Nemesis model (EC JRC 2020). The Nemesis model (a macro-sectoral model with a recursive dynamics) is a decision support tool, helping to make a choice between different policies taking into consideration management, budget and design issues. (European Commission 2018, Akcigit et al. 2022).

The European Commission regularly reviews the implementation, the results and the impacts of the Common Agricultural Policy by applying the common monitoring and evaluation framework (CMEF) (EC DG for Agriculture and Rural Development 2015, European Commission DG Rural Development 2017). CMEF provides indicators (output, result, impact, context indicators) evaluating the implementation against the set objectives of the programme.

In 2023 FAO introduced the concept of true cost accounting (TCA) (FAO 2023). By definition TCA is "A holistic and systemic approach to measuring and valuing the environmental, social, health and economic costs and benefits generated by agrifood systems to facilitate improved decisions by policymakers, businesses, farmers, investors and consumers." TCA helps to uncover hidden costs along the agrifood system and provides a guide for transformation. Hidden cost is defined as "Any cost to individuals or society that is not reflected in the market price of a product or service. It refers to external costs (that is, a negative externality) or economic losses triggered by other market, institutional or policy failures." However, hidden costs do not cover all costs relevant to soil pollution and remediation. While costs associated with pollution (as one of the land degradations), or pesticide exposure was omitted, costs of land-use change and nitrogen emissions were included. In that respect it is important to note that on the one hand, both control of nitrogen

DOI: 10.5281/zenodo.17430539

emission and land-use changes are part of the pollution prevention tools. On the other hand, the omission of the costs was justified not by the inadequacy of the assessment, but rather by data gaps (lack of global datasets, models for estimating cross-country hidden costs), or by intangible values that cannot be monetized. In 2024, consideration was given to improve the assessment of TCA by integrating the pollution costs of pesticide use into the hidden costs (Lord 2024, FAO 2024a).

The above means that if the limitation of data gaps is overcome the TCA assessment could become a valuable method for identifying hidden socioeconomic costs caused by soil pollution (land degradation) not only in relation to the agrifood system but to other sectors as well. During the TCA assessment process the following levers are reviewed: trade and market interventions, (de)coupled subsidies, general services support, laws and regulations behavioural policies, private capital, voluntary standards. All of them are relevant from the point of pollution and its prevention.

FAO has reviewed the hidden costs in 154 countries. Data for all EU member states (except Cyprus, Luxemburg and Malta) are published in the report. It underlines the diversity of member states, and how TCA assessment made at national level allows country specific conditions (soil health relevant, economic, social, cultural conditions, availability of data) to be taken into account. That is crucial for policy design at national and EU level, as implied often in scientific papers.

Pollution prevention requires transformation of all sources and causes (human activities, market, institutional and policy failures) leading to pollution. Prevention transforms the socioeconomic status of the beneficiaries associated with pollution and the negatively affected stakeholders depending on the principles used (polluter pays or beneficiary pays principle in context with fairness and distributional justice), the method of prevention, for example pesticides substituted by weeding robots, changing land management, soft or hard regulation (Banerjee et al. 2021, Congiu and Moscati 2022), to name but a few. There are several studies analysing these complex issues (Rickert 2004).

Actions

- Research addressing the intertwined nature of stakeholders' relationships to soil pollution impacts and policies and the effect of country specific cultural and historical backgrounds relevant to institutional, market, or policy setups and failures in the context of pollution prevention and the need for behavioural change,
- Comprehensive, consistent and comparative research of the existing tools on socioeconomic issues, how both sides are affected by prevention, and how to fill data gaps,
- Further development and improvement of the tools,
- Testing the tools including the test of the TCA assessment in member states with contrasting levels of data to see how it performs under different circumstances,
- Making the socioeconomic impact of soil pollution and its prevention on the beneficiaries and on the negatively affected more transparent and to highlight trade-offs,
- Data collection on the socio-economic status of the exposed and the polluters, and the impact of the preventive measures on those statuses.

Bottlenecks

- Limited acknowledgement and understanding of the intertwined nature of stakeholders' (polluters and exposed to pollution) relationships to soil pollution impacts and policies hinder further development and improvement of the tools, and the identification of trade-offs.
- Lack of cultural context hinders consistent data collection and comparison of data, and to develop adequate tools for addressing socioeconomic issues stemming from soil pollution prevention and remediations.
- Sector-specific approaches hinder the development of an overarching, comprehensive and consistent framework for soil pollution prevention and remediation.

DOI: 10.5281/zenodo.17430539

3.1.3. Impact of soil pollutants (individual and mixtures, short-term and long- term) on human Health

Summary of the Knowledge Gap (Knowledge Gap 3)

Available research clearly shows that soil pollution poses severe risks to human health. People are throughout their life exposed to soil pollutants through different routes. The measure of all the exposures throughout a lifetime is referred to as "the exposome". Drinking water and food contamination, transport of pollutants via dust to places frequented by people (paths, playgrounds, houses, gardens,), ingestion/inhalation of soil particles and dermal exposure are important exposure pathways through which soil pollution can impact human health. Analogous to the research gaps regarding the assessment of the impact of pesticides on the environment, the complete impact of total soil pollution exposure through all exposure routes, taking into account mixture and cumulative effects, chronic low-level exposure, throughout a lifetime (the 'exposome'), on human health remains currently unclear. For example, current risk assessment focuses mostly on e.g. pesticide exposure through food ingestion, while experts point out that exposure via air and skin are important routes of exposure, which are currently not adequately assessed.

State of the Art

A variety of studies have shown the impact of soil pollution on human health. Drinking water and food contamination, transport of pollutants via dust to places frequented by people (paths, playgrounds, houses, gardens, etc...), ingestion/inhalation of soil particles and dermal exposure (Marin Villegas et al. 2019, Chaparro Leal et al. 2018, Govarts et al. 2023) are important exposure pathways through which soil pollution can impact human health. Among the chemicals or groups of chemicals of major public health concern identified by the WHO are Cd, Pb, Hg, dioxin and dioxin-like substances and highly hazardous pesticides, of which residues are transported from polluted soils to food and water bodies. Also pathogens present in soil may contaminate food, with human health risks (e.g. diarrhea, cancers). Health aspects related to soil pollution vary according to land use (e.g. urban soils are characterised by specific problems and challenges, given the concentration of anthropogenic activities concentrated there, and the high population density). Münzel et al. (2024) underline the links between soil and water pollution, and cardiovascular disease. Robust evidence has shown the links between multiple pollutants, such as pesticides, heavy metals, dioxins and toxic synthetic chemicals to increased risk of cardiovascular disease, while some data also suggest an association between micro- and nanoplasic particles and cariodvascular disease. The authors point out that soil pollution diminishes soil's capacity to produce food, causing crop impurities, malnutrition and disease.

People living in areas with a higher concentration of metals and metalloids in soil are linked to the aetiology of some forms of cancer, increased incidence of mental disorder and all-cause cardiovascular diseases mortality (Vieira et al. 2024, European Commission: European Environment, Joint Research Center et al. 2024, Núñez et al. 2017, Ayuso-Álvarez et al. 2019, Ayuso-Álvarez et al. 2022). Higher rates of lung cancer mortality was found in regions with higher concentrations of cadmium or arsenic (Bartnicka et al. 2023). For some locations, this was supported by increased regional mortality rates caused by cancer types associated with these pollutants (Parviainen et al. 2022). An identified knowledge gap underlined in European Commission: European Environment, Joint Research Center et al. (2024) is that most of the identified studies use the total amount of a given pollutant in soil, rather than considering the bioavailable fraction (Hemphill et al. 1991, Zhao et al. 2020). The uptake of metals by plants may pose significant risks to human health.

Research projects show widespread pesticide contamination in soils, air, waterways, indoor dust, animals and humans. However, systematic monitoring data of pesticide residues are not available. A large body of research shows the links between pesticide exposure and a variety of health impacts. Pesticide exposure has been

DOI: 10.5281/zenodo.17430539

linked to various types of cancers (non hodgkin lymphoma, multiple myeloma, prostate cancer, leukemia, breast cancer, kidney and bladder cancer, soft tissue sarcomas, hodgkin's disease, testis cancer, melanoma), respiratory diseases (e.g. asthma), neurodegenerative diseases (Parkinson's disease, Alzheimer's disease), anxiety/depression, thyroid diseases, developmental delays in children and cognitive imparements, cardiovascular diseases, infertility of birth malformations, weakening of immune system and negative impacts on the gut microbiome (Bretveld et al. 2006, Inserm 2021, Nicolopoulou-Stamati et al. 2016, Abou Diwan et al. 2023, Farr et al. 2004, Figueiredo et al. 2021, Gama et al. 2022, Doğanlar et al. 2018, Panzacchi 2025). Certain illnesses, such as types of cancer (in France) and Parkinson's disease (In France, Italy and Germany), have been listed as occupational diseases, due to their high prevalence among farmers and farmworkers (Shan et al. 2023, Bloem and Boonstra 2023, Adhikari and Hartemink 2016, Inserm 2021). Silva et al. (2023) found that 64%, 66% and 76% of pesticide residues found in, respectively, crops, indoor dust and air samples, are linked to adverse human health effects. They found 43% and over 49% of residues in indoor dust and air samples have been linked to highly severe effects (e.g. carcinogenicity, neurotoxicity, endocrine disruption, reproductive/development effects). Similarly to the shortcomings in pesticide risk assessment for the environment, pesticide risk assessment for human health is characterised by extensive shortcomings. Mostly only uptake of pesticides through food is monitored, while exposure routes such as inhalation and uptake through the skin are not, or not well assessed. The uptake through food is underestimating real risks to consumers by not accounting for mixtures. In addition, Hernández et al. (2013)highlighted that the synergistic and mixture effects of pesticides, and the long-term exposure of (low-level) concentrations, are not taken into account in current risk assessment. Co-formulants, which are added to pesticide products, are not assessed. Moreover, different health impacts such as neurological impacts and endocrine disrupting impacts are not adequately, or not, assessed (Bloem and Boonstra 2023). Comprehensive assessments, covering toxicity effects of pesticide mixtures and cumulative effects, long-term low-level exposure, indirect effects, and spatial analysis of long-term pesticide exposure and prevalence of specific health impacts in Europe are needed to assess these impacts further.

Excessive nutrients in soils are linked to important human health risks. For example, nitrogen emission contributes to the development of aerosol and particulate matter air pollutants, impacting human health (European Commission: European Environment, Joint Research Center et al. 2024, Pozzer et al. 2017). Also indirectly, excess nutrients in soil affect human health, through compromising drinking water (Lundin and Nilsson 2021).

It is well documented that the soil deposition of veterinary medicines such as antibiotics and anthelmintics could raises health concerns associated with their plant uptake and translocation to edible plant parts entering the food chain (Navrátilová et al. 2021), and the environmental dispersal of antibiotic resistance genes (Udikovic-Kolic et al. 2014).

Analogous to the impacts on biodiversity and ecosystems, the impacts of soil pollution on human health reach far beyond polluted soils. The widespread drift of soil pollution leads to pollution of water resources (groundwater, drinking water, surface water, the marine environment), to air and indoors (e.g. in houses, schools). Soil pollution leads to the degradation of ecosystem services, with far-reaching impacts on human health. For example, by negatively impacting soil invertebrates and soil microbial communities, pesticide and metal pollution impact carbon cycling and storage (Gunstone et al. 2021, Azarbad et al. 2015, Faggioli et al. 2019). Micro- and nanoplastics also have negative effects on soil properties, with their degradation leading to the release of other contaminants, which can affect soil organisms and plant growth, and accumulate in the food chain (European Commission: European Environment, Joint Research Center et al. 2024). The impact of soil pollution on human health is therefore multi-faceted, as soil pollution not only poses direct health risk due to e.g. dermal absorption, ingestion and inhalation, but also undermines food- and water quality and ecosys-

DOI: 10.5281/zenodo.17430539

tem services, holding important risks for food security (Morgado et al. 2018, European Commission: European Environment, Joint Research Center et al. 2024).

Persistent organic pollutants in soils impact human health (van den Berg et al. 2017). Also, uptake of PAHs through contaminated food is associated with a suspected carcinogenic risk.

Concluding, available research clearly shows that soil pollution poses severe risks to human health. People are throughout their life exposed to soil pollutants and other pollutants through different routes. The measure of all the exposures throughout a lifetime is referred to as "the exposome". Dr. Christopher Wild defined the exposome in 2005 as "every exposure to which an individual is subjected from conception to death" (Westmark 2023). The exposome can be highly variable and evolves throughout the lifespan. Understanding how the exposure to different environmental pollutants throughout a lifetime, including soil pollution, impact human health, is key and represents a major knowledge gap. Drinking water and food contamination, transport of pollutants via dust to places frequented by people (paths, playgrounds, houses, gardens,), ingestion/inhalation of soil particles and dermal exposure are important exposure pathways through which soil pollution can impact human health. Analogous to the research gaps regarding the assessment of the impact of pesticides on the environment, the complete impact of total soil pollution exposure through all exposure routes, taking into account mixture and cumulative effects, chronic low-level exposure, throughout a lifetime (the 'exposome'), on human health remains currently unclear. For example, current risk assessment focuses mostly on e.g. pesticide exposure through food ingestion, while experts point out that exposure via air and skin are important routes of exposure, which are currently not adequately assessed.

Actions

- Ambitiously enhance systematic monitoring of soil pollution, to fill in the extensive gaps on presence of pollutants in soils affecting human health,
- Include in human health risk-assessment long-term, low-level, chronic, cocktail/ mixtures and cumulative/synergistic effects (exposure to multicontaminants), as well as the indirect impacts though the impacts on e.g. ecosystem functioning/ services, to integratively assess the impact on human health. Include the 'Exposome' in risk assessment,
- Include all relevant studies in risk assessment, and ensure transparency,
- Research/action on prevention and remediation of soil pollution, e.g. transitioning to ecological farming methods and investing in nature-based solutions,
- Include impact of soil pollution on human health, on ecosystem services, in modelling to support policy making decisions,
- Data collection and analysis of individual substances on human health (exposure routes, toxicological properties, the exposome).

Bottlenecks

- The high complexity of soil pollutant mixtures and (indirect) effects on human health hinders systematic monitoring and health-risk assessment,
- Lack of systemized monitoring, and limited capacity leads to data gaps which hinder the determination of the level and spatial extent of pollutants in EU soils, both for point-source and diffuse pollution affecting human health,
- The various and varying attitudes and perceptions of actors involved in soil pollution hinder the directing and attributing needed means and efforts to the assessment of the impact of soil pollution on human health and the development and application of preventive measures and remediation practices.

3.2. Other prioritized Knowledge Gaps

This sections describes the other 7 prioritized knowledge gaps, which were identified as part of the 10 priority knowledge gaps, next to the 3 key knowledge gaps described above.

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3.2.1. (Knowledge gap 4) - Data gaps on soil pollution and lack of systemized monitoring

Summary of the Knowledge Gap

Despite the extensive knowledge on pollutants and their impacts, a clear lack of data on soil pollution still exists. It is linked to a lack of data on soil pollution and systemized monitoring frameworks, which are needed to assess the scope and possible impacts of soil pollution, and to develop management and policy tools.

State of the Art

There are several ways to gather data, including monitoring systems. There are high- resolution on targeted areas (e.g. industrial areas), and low-resolution of general purpose monitoring schemes. While general monitoring schemes like EU's LUCAS and GEMAS have contributed to soil pollution data, specifically on metals and pesticides, the full extent of most soil pollutants remains unknown. This includes newly emerging contaminants, and their possible (future) impact on soil functioning. Data and monitoring of key groups of soil pollutants (e.g. pesticides, pharmaceuticals, biocides, metals, PCBs, PAHs, TPHs, PFAS, micro- and nano plastics, pollutants in sewage sludge and relevant metabolites/by-products) is key to assess soil pollution levels and risks, and monitor management strategies to achieve healthy soils. For many substances, there is a lack of widely accepted determination/ quantification methods in soils and soil organisms. Challenges include associated risks, comparability and error determination.

There is much diversity and complexity in the monitoring of different pollutants. Micro- and nano-plastics, as well as many emerging pollutants, are challenging to monitor. Although prioritization approaches and practical feasibility are prerequisites for effective gathering of data and monitoring, it is overall essential to monitor as many soil components/contaminants as possible. Materials that are currently not considered pollutants, could pose extensive problems in the future.

Past experience has shown a long delay between substances ending up in soils, and the realisation of their negative impacts, resulting in far-reaching, long-term challenges for ecosystems, their services and human health. Currently, there is a lack of understanding of the scope of contaminants/pollutants, including newly emerging contaminants, and their possible (future) impact on soil functioning. Large data gaps exist regarding the presence of emerging pollutants (e.g. pharmaceuticals, endocrine disruptors, hormones, micropollutants (e.g. microplastics) in soils, their behaviour in the environment and their toxicity, transport and bioaccumulation properties in humans. Available research shows that emerging pollutants can raise pollutants of concern, involving high risks for the environment and human health (Vieira et al. 2024, Rodríguez-Eugenio et al. 2018, Covaci et al. 2011). Enhancing and implementing methodologies to measure and predict the presence and impact of newly emerging contaminants are needed.

Data gap issuses are relevant to all types of land uses. Urban soil pollution has been documented through several cases, but has been overall poorly studied. Urban soil pollution is associated with specific challenges related to among other issues, human health (Guillén et al. 2022), water quality (e.g. groundwater pollution OECD 2023b) and risks for pollution of surrounding regions (Liu et al. 2023). Insights in the full impact of urban soil pollution are lacking, as well as clear frameworks and initiatives to tackle urban soil pollution.

Actions

- Review and comparative analysis of EU and national data on soil pollutions (existing and emerging pollutants),
- Review of methodologies, and monitoring systems aimed at identifying site specificities (abiotic and biotic conditions), and shedding light on member state's priorities, economic, institutional, and regulatory constraints/ limitations,
- Development of a monitoring framework and harmonisation of member states methodologies without affecting member states' interest and priorities by the standardization,

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- Establishment of an open access database with risk relevance on emerging pollutants to promote well-informed decision-making.

Bottleneck

- Lack of standardised monitoring frameworks and methodologies for measuring pollutants hinders comparative analysis at EU level, the establishment and operation of consistent databases, robust risk assessment and well-informed decision-making.
- High costs and institutional barriers hinder development of monitoring frameworks, harmonisation and comparative analysis.

3.2.2. (Knowledge Gap 5) - Technical/practical tools to remediate soil pollution and restore soils

Summary of the Knowledge Gap

There is need for further development of remediation and restoration techniques, and for further knowledge on how traditional and alternative tools can be effectively and efficiently combined to meet set soil health targets for current and future potential land use. An important aspect is that legislation does not take into account all soil pollution and associated risks, leading to a lack of focus on remediation techniques which focus on tackling pollutant mixtures and emerging pollutants and on restoration. In practice, laboratory analytical programs often provide analysis only for those pollutants listed in the legislation. In this regard, there is a lack of a readily available open access database on new/state-of-the-art techniques/protocols, and new emerging pollutants, in order to support everyday decision-making on remediation.

State of the Art

Chemicals or mixtures of chemicals released into the environment - including soil pollutants - pose an actual risk to soil functions and also to ecological and human receptors. Currently, technical/practical tools have been developed in the light of risk- based land management strategies and the corresponding risk-based soil screening values (risk-based SSV) reflecting on the potential function and future use of the land after remediation (EEA 2023a). There has been a significant shift in remediation technologies and removal of pollutants from soil. Traditional remediation practices (physicochemical technologies) are substituted or combined with alternative techniques (Phang et al. 2024), such as addressing management practices, crop use and the use of microbial technologies. However, there is a need for further research and development to improve remediation effectiveness. Methods include phytoremediation, phytoextraction, phytostabiliziation, phytovolatization, phytodegradation (Sharma et al. 2023) phytomanagement (Evangelou et al. 2015), bioremediation (Sales da Silva et al. 2020, Jiang et al. 2022) and vermiremediation (Xiao et al. 2022).

Specific challenges are associated with soils contaminated with multiple pollutants. The interaction between organic and inorganic pollutants can change bioavailabity and solubility of pollutants and their biotoxicity and biological metabolic processes. (Vieira et al. 2024). For pollutants that are relatively new to the environment, such as PFAS, important challenges remain due to unknown pathways of degradation. Also, competition or joint adsorption on binding sites poses a challenge. For mixed contaminated soils, successful combinations of physicochemical and biological remediation techniques have been discussed, and the positive synergistic impact underlined, however, more research is needed (Aparicio et al. 2022, Lacalle et al. 2020). Microbial technologies carry great potential, however, still need further development regarding increasing efficiency. The process is highly time consuming, which is considered a significant bottleneck in the field of bioremediation. More research is needed on the potential of nature-based solutions and the use of microorganisms for bioremediation processes.

As stakeholders highlighted, the daily practice in the investigation and assessment of impacts uses a set of tools to evaluate the actual risks posed by contaminants or combinations of chemicals. These tools include different threshold- limit

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values for organic and inorganic chemicals, and also numerical models for qualitative risk assessment processes in order to evaluate the actual risks of the impacts. The practical application of this evaluation and assessment framework needs clear and sound scientific background as a basis for the evaluation and assessment of the rate and risk of the impacts. In practice, the list of recognized contaminants is amended regularly with compounds that were not recognized as priority pollutants or were not focused on before such the PFAS-PFOS compounds. Typically, laboratory analytical programs of environmental assessments (both for soil or for groundwater) include those compounds that are listed in the relevant legislation. In this way, it may easily happen that samples contain chemicals which are of potential concern remain under the radar, if those chemicals are not yet taken up in legislations. This may lead to wrong conclusions when evaluating the results.

A similar example is soil gas as an environmental indicator or element. Many organic compounds, once released into the soil, tend to evaporate into the soil gas above the groundwater level - in the so-called unsaturated zone. These vapours may affect the multifunctional properties of the top fertile layers of the soil and may also pose a human health risk if migrating into confined spaces like cellars or houses. In many cases this type of risk is leading to the need of an engineering intervention. Yet, soil gas is not even mentioned in many countries in the relevant legislation, as a factor to be monitored or considered. In general, more research is needed to improve efficiency, feasibility, costs and time efficiency of remediation techniques for a variety of different contaminants and soil conditions.

Actions

- Research on the effect of mixtures and emerging pollutants,
- Research on the further development of remediation techniques
- Research on how to improve efficiency and effectiveness of alternative, nature-based techniques, including the review of how traditional and alternative methods could be combined,
- Review and comparative analysis of economic, institutional and policy framework of remediations and the technical solutions,
- Development and introduction of a coordinated mechanism and a task on national and EU level to establish and maintain an open access database with a regular update of scientific research to support the everyday decisions on remediation,
- Review of the laboratory protocols and develop a procedure on how to update them for emerging pollutants.

Bottleneck

- Nature-based solutions are often time-consuming which hinders their further development and application, as well as the development and uptake of nature- based solutions in combination with traditional methods and techniques.
- Limited market interest for alternative remediations solutions hinders research and development of alternative methods.
- Outdated laboratory practices hinder the adoption of new techniques and the assessment of the effect of pollutant mixtures and emerging pollutants.

3.2.3. (Knowledge Gap 6) - Behaviour/transportation and fate of soil pollutants and link of soil pollution with water and air

Summary of the Knowledge Gap

Soil pollution contributes to water and air pollution, and pollutants transported by air and water can cause soil pollution, particularly diffuse pollution. Extensive knowledge gaps exist concerning the partitioning of pollutants in different physical phases, and the behaviour, transportation and fate of many soil pollutants in soil, water and air. These three compartments hence need to be adequately assessed to evaluate (the impact of) diffuse soil pollution, demanding complex analysis.

DOI: 10.5281/zenodo.17430539

State of the Art

Soil pollution is a major cause of groundwater and surface water contamination. Identified pathways from farm lands include: erosion and water body siltation, runoff contaminated with fresh manure, fertilizers or pesticides, and saline irrigation drainage water affecting downstream ecology, nitrogen and phosphorus overuse (Drechsel et al. 2023).

In urban areas, solid municipal waste dumps pose a threat to groundwater with a significant negative effect on the socioeconomic status of people residing nearby the dumpsites (Parameswari et al. 2012). NOx soil emissions can have important impacts on air quality (European Commission: European Environment, Joint Research Center et al. 2024). Local pollution (e.g. contaminated sites) is, via transportation processes, also often linked to diffuse pollution. The analysis of contaminated soil samples of 112 ecosystems across the globe (including Antarctica), comparing the contamination level between urban greenspaces and nearby natural sites, proved the transportation of soil pollutants, and its global effect (Liu et al. 2023). At the same time, pollutants found in water bodies and in the air can be transported to soils, through precipitation or deposition processes. The interlinkages of the different matrices entail important consequences for management of pollution. For example, when groundwater is contaminated, the costs and complexity of bioremediation of soils are also greatly increased. In addition, insufficient knowledge of bioaccumulation and bioavailability of soil pollutants limits our understanding of associated risks. Accumulation of contaminants in one soil organism (e.g. earthworm) can be transferred through the soil foodweb to other trophic levels and reach aboveground organisms (e.g. birds) (FAO and UNEP 2021). The soil polluting human activity (the pollutant used, the timing and the conditions of the application of the pollutant) has an impact on the behaviour, transport and fate of soil pollutants, through its effects on soil functions, and influenced by the abiotic and biotic conditions of the specific site.

Processes of transportation (e.g. wind erosion) and air-water-soil interactions are highly dependent on soil characteristics and climatic conditions. This knowledge is essential for preventing pollution. The integration of such knowledge into decision support systems is crucial for actual prevention of water and air pollution. An example of such a tool is the ‘pesticide fate tool’ developed during the LandSupport project for the assessment of groundwater vulnerability to specific pesticides, and to guide decision makers in making the right choice in respect of site specificity (Bancheri et al. 2022). This underlines, that site-specific evaluations are needed. The EC’s monitoring report of 2022 on the “zero pollution” ambition (European Commission 2022a) and the the Reports of the European Court of Auditors (European Court of Auditors 2020a, European Court of Auditors 2020b) underline the need to address the influence of human activities on soil pollutants.

Extensive knowledge gaps still exist concerning the partitioning of pollutants in different physical phases, and the behaviour, transportation and fate of many soil pollutants in soil, water and air. These three compartments hence need to be adequately assessed to evaluate (the impact of) diffuse soil pollution, demanding complex analysis (Geissen et al. 2021).

Action

- New research and research update on the partitioning of pollutants in different physical phases, and the behaviour, transportation and fate of existing and emerging soil pollutants in soil, water and air, taking into account site specific characteristics,
- Comprehensive and comparative review of human activities’ impact on soil pollutant’s move among the three compartments,
- Comparative review of the existing decision support systems to assess their ability to promote preventive decision making.

Bottleneck

- Institutional barriers (e.g. lack of personnel and laboratory facilities) hinder new research and research updates on pollutants’ characteristics and partitioning in different matrices.

DOI: 10.5281/zenodo.17430539

3.2.4.(Knowledge gap 7) - Baseline, Indicators/descriptors and quality thresholds/criteria

Summary of the Knowledge Gap

There is a need for baselines and environmental quality standards for the assessment and monitoring of soil health. Natural background concentrations and natural variability of soils, the physical and chemical state, and soil biodiversity are relevant in this regard. Detailed soil monitoring data are missing. Soil health descriptors and accompanying quality thresholds should be established, including a robust set of biodiversity indicators, to allow for systematic and high quality monitoring and soil health assessment.

State of the Art

Setting up the baseline at EU level, assessing different local contexts, and taking into account the industry specific hazards (UNEP 2024, Yacoub et al. 2014) is a prerequisite to effectively implement actions and effective mechanisms to monitor progress towards targets/implementation of measures. It is important to note that the impacts of soil pollutants are site specific, as they depend on soil characteristics and environmental conditions, affecting also their transformation (reactions, fragmentation, etc.), while transport can occur and affect other areas, with other specific conditions.

Pollution is one of the many aspects which can make a soil unhealthy: a polluted soil is considered an unhealthy soil. There are however sites where high contamination level is not due to human activities. It is argued that in such a case soil should not be considered unhealthy, if the natural equilibrium is not disturbed (Vieira et al. 2024).

Different indicators/descriptors/indices and accompanying quality thresholds/criteria for assessing soil health have been described in scientific literature. Vieira et al. (2024) refer to the use of different pollution indices (Brtnický et al. 2019, Ferreira et al. 2022, Kowalska et al. 2018, Ferguson 1999) while Sun et al. (2020) compare the different approaches of China and the UK. Kotschik et al. (2024) underline the need to define and implement biodiversity indicators. Policy frameworks reflect on that diversity (Ferguson 1999, Deseo et al. 2001, EEA 2023a). Andres et al. (2022) suggested to include chemical residues, effect data for soil organisms in combination with occuring habitats to describe effects of chemicals on soil organisms.

However, a lack of understanding and agreement remains on which indicators and criteria to apply to define and assess (the progress towards) soil health, levels of soil degradation, and identify soils which need urgent restoration (e.g. trigger and action values), and prioritisation.

Importantly, robust indicators to monitor effectiveness of soil management (prevention and restoration) strategies to restore soil health are needed. However, before starting monitoring programs of chemical residues in soils, the sets of to be monitored chemicals and other pollution indicators, as well as the sampling methods needs to be defined. Soil organisms such as Acari and Collembola and earthworms have been suggested to be potentially good indicators to assess soil pollution and effectiveness of management strategies (Sahana 2010, Xiao et al. 2022). Moreover, also nematodes are candidates for indicators (FAO et al. 2020).

In order to efficiently set and achieve targets, a clear understanding of baselines, indicators and quality thresholds is key.

Actions

- Review and comparative analysis of the baselines with consideration given to site specificity and natural contamination level,
- Gather knowledge on expectation abundances and diversity of in-soil biodiversity - start with earthworms and develop indicators and criteria for determining **chemical and biological** soil health in view of soil diversity,
- Review and development of environmental quality standards for pollution **and soil biodiversity** monitoring .

Bottleneck

- Ambiguity of the definition of soil health and its indicators hinders comparative analysis and establishing clear baselines, and harmonizing environmental quality standards and targets.

DOI: 10.5281/zenodo.17430539

3.2.5. (Knowledge Gap 8) - Overall impact of soil pollution on wider ecosystem functioning (beyond soils)

Summary of the Knowledge Gap

The relationship between soil pollution and ecosystem functioning is not fully understood and/or acknowledged, partly due to insufficient available data. Thus there is a lack of a framework that addresses the aspects related to the link between soil pollution, prevention and ecosystem functioning in a spatiotemporal context. Soil functions play a key role in why and how soil pollution affects ecosystem functioning. While that role has been extensively researched in a sector specific context, there is a lack of a holistic approach that simultaneously focusses on soil pollution and prevention/remediation/ restoration choices.

State of the Art

'*Ecosystem functioning refers to the state or trajectory of ecosystems in terms of innate pathways and fluxes of energy, matter, and information occurring through essential ecosystem processes, such as productivity, nutrient and biogeochemical cycling, and ecological network dynamics, from which is derived the stability that supports ecosystem complexity at a larger scale*' (Correia and Lopes 2023). Soil pollution threatens that stability. Numerous studies have emphasised the importance and severity of the negative impact of soil pollution on the environment, on food security and human health (most recently European Commission: European Environment, Joint Research Center et al. 2024, Vieira et al. 2024).

The need for a comprehensive soil protection has been recognised since the 1990s and the EU acted upon it in the early years of 2000 by adopting thematic strategies addressing all the issues mentioned (Semikolennykh 2008). Since then, science has constantly reinforced, provided new insights, and highlighted the growing severity of human-driven pollution induced disturbance of the ecosystem functioning and its consequences, and the sectoral responses to some of the consequences (for agriculture: FAO 2023, FAO 2024a, Lord 2024, for industry: Obeng-Odoom 2023, Liu et al. 2023). The adoption of the Green Deal and the Zero Pollution Action Plan is the acknowledgement of that threat.

Nature-based remediation technologies use ecosystem services building on the support of soil functions. Thus, if soil functions are put in the centre, four main ways can be identified through which soil pollution affects directly and/or indirectly the ecosystem functioning: **1.** the impairment of soil functions due to pollution causing negative changes in soil's physical, chemical properties and its functional biodiversity which are key to the provision of ecosystem services. **2.** soil function that provides for the bioavailability of pollutants, making plant uptake possible, leading to accumulation of pollutants in the food chain, **3.** the transport of pollutants by water and air, **4.** intentional use of soil filtering/ detoxicating and/or plant uptake functions for remediation purposes. Therefore, also when making decisions on remediation technology, decision makers should consider the impact of remediation on the overall ecosystem functioning. All four pathways affect the spatiotemporal scale of soil pollution.

While it is important to promote research shedding light on the links between soil pollution and ecosystem functioning, and innovation of new technologies and land and soil management approaches, the main question remains how to transform our economy (all sectors) to ensure soil health and soil pollution prevention are taken effectively into account, and to ensure the protection of ecosystem functioning as the basis of human existence.

Actions

- Research on the links between soil pollution and ecosystem functioning,
- Review and update the existing data in order to establish the relationship between pollution and ecosystem functioning,
- Development of a comprehensive analytical framework to address spatiotemporal economic, institutional and policy failures and

DOI: 10.5281/zenodo.17430539

identify decision making levels in order to reach prevention of pollution.
- Systematic monitoring of changes in ecosystem functioning due to soil pollution and/or prevention measures including restoration and remediation.

Bottleneck

- Differences in stakeholders' perception on the relationship between soil pollution and ecosystem functioning and on the need for a holistic approach hinder prevention oriented policy development and decision making.,
- Sectoral interests related to soil pollution and prevention lead to policy fragmentation and contradiction, along with disproportionate allocation and/or distortion of financial resources and hinder the implementation of prevention oriented policies.
- Differences in level of detail, sources (different sectors, spatial and time scales, e tc....) and structure of data hinder a holistic and overarching framework addressing the impact of prevention of soil pollution and remediation/restoration on ecosystem functioning.

3.2.6. (Knowledge Gap 9) - Technical/practical tools to prevent agricultural soil pollution

Summary of the Knowledge Gap

Although a wide array of management practices and technologies, including IPM strategies, agroecological practices, agroforestry, conservation and regenerative practices, biocontrol, monitoring and precision technologies are available to reduce, minimise or eliminate agricultural soil pollution and restore soil health for many cropping systems, there is still a need to further optimise and develop these existing practices, methodologies and technologies. There is a need for the compilation and translation of best available practices to minimise soil pollution and restoration into crop-specific and pedoclimatic integrated pest/crop management rules. Further research is still needed to develop and/or optimise these sustainable soil management practices and technologies for all cropping systems, climatic and environmental conditions and pests. The to be developed/compiled sustainable soil management rules should be science-based; practice-proofed and built on experiences in field projects gathering independent scientific expertise and practice. The use of functional biodiversity in increasing natural pest control and decreasing dependence on pesticides is a complex field, which needs specialised adaptation to specific cropping systems and environments. Also, adequate risk assessment systems are needed to effectively and efficiently assess new technologies.

State of the Art

Integrated Pest Management (IPM) is based on preventative measures, increasing natural pest control (beneficial organisms) and the resilience of cropping systems against pests, while only using chemical pesticides when all other methods have been exhausted and failed. In this knowledge gap 9, we highlight a few key aspects of preventative agricultural measures on which research and innovation should focus, to enhance their further development and optimisation.

- **IPM** is considered key in reducing agricultural soil pollution and restoring soil health. Although very developed for a wide variety of cropping systems, more research is indicated to further develop and optimise IPM for all farming and cropping systems, and on the integrative assessment of the full range of benefits associated with IPM, regarding e.g. soil biodiversity and (soil) ecosystem services.
- E.g. Deguine et al. (2021)have highlighted the lack of research on IPM/gaps in research programs. They highlight that integrative, interdisciplinary research, e.g. on soil and aboveground biodiversity and interactions with agroecosystem components, landscape ecology and its renewed scales are still mostly missing (Begg et al. 2017, Brewer and Goodell 2012, Redlich et al. 2018). The authors state that most research on IPM tends to list and describe

DOI: 10.5281/zenodo.17430539

tactical solutions separately, in specific contexts (e.g. focusing on a single pest, single crop, specific context), rather than scientifically understanding the advantage of using them together to harness synergy. There is a need for more integrative assessments, which take into account different pests and all management aspects. Important projects which have focused/are focussing on taking into account all aspects of IPM are the European 'Pure' project on field crops (Vasileiadis et al. 2017 Vasileiadis et al. 2018, Lescourret 2017) and the European IPM works project.

- **Agroecology** encompasses the whole food system, and is based on sustainable use of local renewable resources, local farmers' knowledge and priorities, wise use of biodiversity to provide ecosystem services and resilience, and solutions that provide multiple benefits (environmental, economic, social) from local to global. It is based on 13 principles, including maintaining and enhancing soil health and biodiversity (Agroecology Europe 2025). Available research shows the benefits of agroecology for the environment, including soil health, food security and nutrition (Nicholls and and Altieri 2018, Bezner Kerr et al. 2021). More research is needed on best agroecological practices for all relevant EU crops and farming systems. Specific identified research needs to optimise agroecological (and IPM) practices, as described by Deguine (2023), include research on sustainable seed resources and breeding, the electrochemical soil- plant health model and microbiota-mediated plant-soil feedback.
- **Agroforestry** is associated with reductions in soil pollution, e.g. through the minimisation of pesticide use and risk, and the reduction of excess nitrogen and phosphorus residues in soil, effectively contributing to the restoration of soil health, while also reducing the runoff/drift of soil pollution.
- **Biocontrol** measures include the use of macrobials, microbioals, natural substances or semiochemicals to prevent and control pests. Biocontrol has shown to be very effective in a wide range of cropping systems, and decreases in the use of chemicals in the field, as well as decreasing pressure on soils, aboveground biodiversity and human health. The effectiveness of biocontrol depends also on the functional biodiversity present at field and landscape level, which can greatly contribute to the effectiveness of biocontrol. More research is needed on the development of biocontrol agents for a wider variety of pests and cropping systems, and on the interactions between all categories of biocontrol and biodiversity. Also specifically on the impacts of biocontrol on soil health, more research is needed.
- **Mechanical weeding technology/robots**: Nichols et al. (2015)described weed dynamics and the principles of conservation agriculture, combining no-till, crop rotation and surface residue, while underlining the need for further research on tillage-residue interactions and stacked rotation. Jiao et al. (2024) and Lytridis and Pachidis (2024) describe the advances in ground robotic technologies for site- specific weed management. They highlight the importance and significant promise of the technology, and the need for specifically more research on weed identification for real-time in open-field conditions, and combined application of mechanical and laserweeding.
- **Monitoring technology**: Promising research has been done on the monitoring of plant and soil health using technology such as drones, leading to effective application and these practices being applied more widely. More research is still indicated, e.g. regarding the detection of diseases without visible symptoms. While more research already focused on fungal pests, less research has been done for virus, nematic and abiotic diseases. Some crops/fruits, such as grape and watermelon have been researched more than others. While more studies use field images, less studies use leaf or plant images. Therefore, research on small- scale objects such as leaves/individual plants will require higher- resolution visual inspections.

DOI: 10.5281/zenodo.17430539

Actions

- Research on IPM, agroecological, agroforestry, and regenerative and conservation practices, to optimise IPM for all relevant EU crops/pests, and to assess all benefits of IPM at landscape-scale level, in framework of soil health, soil and aboveground biodiversity and ecosystem services,
- Research on biocontrol measures, to extend biocontrol options for a wider variety of pests and cropping systems,
- Research on technology/robotics to enhance monitoring of pests/crop health/soil health and mechanical weeding,
- Further expanding, connecting and coordinating living labs, lighthouses and regional networks working on IPM, agroecology, agroforestry, conservation/ regenerative agriculture, to expand testing of sustainable agricultural practices, which minimise or eliminate soil pollution and effectively restore soils,
- Research on 'system innovation', 'system shifts', and the design of alternative cropping and farming systems at regional/landscape level which effectively reduce soil pollution and restore soils.

Bottlenecks

- Diversity in cropping systems, pests, and conditions and farming systems in the EU challenges the development of preventive measures for all farming systems and environmental conditions
- Lack of effective implementation and enforcement of environmental legislation and effective spending of public funds, leading to a lack of clear incentives, drivers and obligations for further development and optimisation of sustainable cropping practices,
- Fragmentation of projects, initiatives and networks working on sustainable agricultural soil management practices hinders the shift to wide implementation of soil health and prevention oriented agricultural practices.
- Conflicts of interests between e.g. agrochemical companies and further development and optimisation of agronomic practices minimising inputs/soil pollution hinder the implementation of preventative and soil health oriented policies.

3.2.7. (Knowledge Gap 10) Knowledge gaps regarding the implementation and upscaling of preventative measures to to address agricultural soil pollution

Summary of Knowledge Gap

While a wide variety of agronomic practices which effectively reduce, minimise or eliminate soil pollution are available (see above), their widescale implementation is still largely lacking. As mentioned above, despite IPM being mandatory in the EU through the Sustainable use of Pesticides Regulation since 2014, multiple analyses of EU bodies have pointed to the lack of implementation of IPM since then. Also the implementation of biocontrol, agroecological, agroforestry, regenerative and conservation practices is lacking. Multiple knowledge gaps still exist regarding the existing implementation gaps related to sustainable soil management practices in agriculture.

State of the Art

IPM is mandatory in the EU since 2014, through the sustainable use of pesticides directive (European Parliament and of the Council 2009, SUD). IPM, as formulated in the SUD, entails the growth of a healthy crop with the least possible disruption to agro- ecosystems, and encouraging natural pest control mechanisms. IPM requires the use of practices and products with the lowest risk to human health and the environment. Although many farmers throughout Europe have been very successfully applying IPM and preventative, low-input and nature-inclusive agricultural practices, while maintaining stable yield and profitability, wide-scale implementation has been lacking (Mora et al. 2023), as was mentioned in the introduction above. Knowledge gap 10 elaborates further on the knowledge gap related to lack of implementation of available practices.

DOI: 10.5281/zenodo.17430539

Available research shows that IPM, and agroecological and organic practices are associated with environmental benefits, including for soil health, and associated with stable yields and profitability, frequently increasing profitability. Nandillon et al. (2024) studied 1000 commercial farms in the French DEPHY network and found no correlation between the reduction of pesticide use and changes in economic performance. van der Ploeg et al. (2019) showed that agroecology has a huge potential in offering farmers more sustainable production of healthier food while improving farmer's incomes. Also Mouratiadou et al. (2024) concluded that agroecological practices are associated more often with positive socio-economic outcomes, although magnitude, temporal aspects and success factors related to the outcomes, as well as trade-offs and system-level effects need further assessment. Lechenet et al. (2017) showed that pesticide use can be greatly reduced through the adoption of different production techniques, and that low pesticide use rarely decreases productivity and profitability in arable farms .Furlan and Kreutzweiser (2015). The European Alliance for Regenerative Agriculture found that regenerative practices led to a higher full productivitiy, higher phtosynthesis, higher soil cover and higher pland diversity, while using 61% less syntetic nitrogen fertiliser and 75% less pesticides (based on the Pesticide Load Indicator), while only slightly reducing yield, and increasing gross margin per hectare with 20% (European Alliance for Regenerative Agriculture (EARA) 2025).

However, despite available research on the success and effectiveness of IPM and agroecological practices, the widespread implementation of sustainable soil management practices, which minimize soil pollution, is lacking.

Soil pollution is associated with many "lock-in mechanisms". Lock-in mechanisms can be described as the barriers and underlying mechanisms that are holding back the transition towards decreasing or preventing soil pollution. The lock-in mechanisms of pesticide use were analyzed elaborately in the framework of the Sprint project (Frelih-Larsen and Sprint project 2022). These lock-in mechanisms include factors related to farmer's perceptions and views (Vanino et al. 2022), agronomy and research, economics, knowledge and awareness and policy and regulation. The fact that policy, funding and infrastructure mechanisms are focused on supporting a limited set of farming models and major crops poses also an important bottleneck. Current agricultural legislation and funding does not secure linkages between funding and protection of the environment and enhancement of ecosystem services: the lack of linkage between the Common Agricultural Policy funding and the implementation of IPM/ICM and restoration of soil health/minimisation of soil pollution form an important barrier. Barriers to large-scale adoption of IPM have also been identified by Deguine et al. (2021): lack of knowledge, risk aversion, conflicts of interests between agricultural advisers and the lobbying of agrochemical companies, lack of technologies adapted to local contexts, lack of clear and effective policies, lack of collective and interdisciplinary action. Furlan and Kreutzweiser (2015) showed that mutual funds are a key tool for IPM implementation, illustrating this by focusing on the use of insecticides for maize production in Italy.

Lack of implementation of IPM is also linked to the lack of concrete crop-specific rules and guidelines. The EC has recently published a database of 1300 examples of practices, techniques and technologies for IPM (European Commission 2023b), including 273 crop-specific guidelines, accompanied by a study assessing their effectiveness. However, there is a need for further development of this database, to complement it with all available knowledge and existing IPM practices, and to further transform it into a user-friendly database, which can be readily used by farmers throughout Europe, selecting appropriate best available IPM measures for their cropping system and pedoclimate conditions. The European Project Agrowise focuses on the practical implementation of IPM, the development of crop-specific rules and the further development/ expansion/ improvement of the IPM toolbox.

Also, the supporting framework to implement practices, such as independent (from business interest) advisory systems, and hence access of farmers to alternative management techniques, are absolutely key in implementing available practices much more widely. However, (access

DOI: 10.5281/zenodo.17430539

to) independent, high expertise advisory services on IPM and sustainable soil management practices have been lacking in most member states.

Nicholls and and Altieri (2018) find that the revival of traditional agricultural systems can offer promising models of sustainability and resilience, and that the creation of lighthouses, which can offer knowledge sharing and peer-to-peer learning across farming communities, are key pathways to effective implementation of agroecology. The IPM works program is an example of very successful implementation of IPM through the organisation of regional hubs, coordinated by hub coordinators, which allow for regional implementation of IPM, trial-and-error and knowledge exchange.

The expertise gained, and lessons learned through different initiatives involving the reduction of soil pollution and enhancement of soil restoration, such as projects fostering the implementation IPM, agroecological practices, and organic agriculture, should be taken into account. This information should contribute to an analysis on which initiatives and supporting conditions are effective would still be needed to increase uptake of good practices throughout Europe.

Actions

- Research on the effective implementation of IPM, agroecology and sustainable soil management practices,
- Invest funds in the further development, coordination, expansion and connection of regional networks of farmers/lighthouses/living labs working on the practical implementation of sustainable agronomic practices,
- Research on needed policy action/implementation/enforcement to ensure alignment of policies and public funds with environmental objectives,
- Foster the development of coordinated, independent advisory systems throughout Europe, through the creation of active, living knowledge sharing networks on best available (implementation) practices,
- Research on the development of crop- and sector- specific IPM rules, based on scientific expertise and best available practices, to ensure the effective implementation of IPM
- Further develop a toolbox with best available IPM, agroecological and sustainable soil management practices,
- Research on key socio-economic drivers, including on insurance mechanisms and integration/inclusion of the whole foodchain, to ensure the effective uptake of sustainable soil management practices/IPM.

Bottlenecks

- Lack of effective implementation/enforcement of current legislation and lack of linkages between environmental objectives and public funding hinder changes and shift towards wide implementation of soil health and prevention oriented agricultural practices .
- Fragmentation of legislation at both national and international level and of existing initiatives (projects, EU/regional networks/national/local networks, etc.…) focused on the implementation of sustainable agronomic practices lead to inefficient allocation of resources and hinder shift to prevention and soil health oriented agricultural practices.
- The complexity of the food chain, and accompanying challenges in involving the whole food chain in fostering and ensuring the implementation of sustainable soil management, hinder the shift to soil health-oriented agricultural practices.
- Lock-in mechanism of agricultural soil pollution (e.g. farmers' perception and views on soil pollution, then existing framework of input providers, farmers, processing industry and retail, the current system of allocation of agricultural funding, etc.…) hinder the implementation of prevention and soil health oriented agricultural policy.

3.3. Overview of knowledge gaps

An overview of the 10 knowledge gaps described above, as well of the other knowledge gaps which were identified can found under Suppl. material 1. The table summarizes the knowledge gaps, their types and relevant land uses, actions which

DOI: 10.5281/zenodo.17430539

Table 6. shows the links between Figure 3. and Annexes of SML.

Figure 3.	Annexes of SML
1) Soil pollution	**Annex I** Soil Descriptors, Criteria for Healthy Soil Condition, and Land Take and Soil Sealing Indicators
2) Effects of pollution	**Annex II** Methodologies **Annex VI** Phases and Requirements of Site-specific Risk Assessment **Annex VII** Content of Register of Potentially Contaminated Sites and Contaminated Sites
3) Solutions to Soil Pollution	**Annex III.** Sustainable Soil Management Principles → was deleted during the negotiations of the EU Parliament and the EU Council **Annex IV** Programmes, Plans, Targets and Measures referred to in Article 10 **Annex V** Indicative List of Risk Reduction Measures **Annex VI** Phases and Requirements of Site-specific Risk Assessment

are recommended to address these knowledge gaps, including the associated time frames, as well as bottlenecks which may hamper these recommended actions.

Further Steps/Notes

Next steps of the PRTT's work include:

- Continuation of the stakeholder-involved iterative process, where the list of knowledge gaps and their prioritisation, actions and bottlenecks will be revisited, updated and complemented, to arrive to a final set of 10 prioritised knowledge gaps, with accompanying actions and bottlenecks, and an updated list of additional knowledge gaps.
- The step above will potentially include the identification of additional knowledge gaps, which have not yet been prioritised nor listed among the additional list.
- Based on the updated list of knowledge gaps, actions and bottlenecks, which will result from the further iterative process described above, the document, will be further developed and optimised, taking into account feedback from stakeholders, reviewers and further literature review.
- Certain themes relevant to all three domains of the conceptual framework still need further inclusion and development, e.g. the various aspects of decision- making related to forestry, urban areas/contaminated sites, tools to change behaviours, nutrient management, the application of principles. The PRTT will further consult with experts/stakeholders on these specific topics, to strenghten these topics in the next update of the document.
- The PRTT will further develop the aspect of definitions related to soil pollution, specifically regarding how different definitions will have different consequences.
- In addition to the knowledge gaps, actions to solve these knowledge gaps and bottlenecks that may hinder these actions, the further work in the PRTT will included the identificaiton of the actions needed to tackle the identified bottlenecks.

Annexes

Supplementary tables

Monitoring requirements of the SML are set in the Annexes of the SML proposal (European Commission 2023a). Table 6. below clarifies the relationship between the Annexes of the EU SML proposal and the conceptual framework (Fig. 3) of this outlook document.

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DOI: 10.5281/zenodo.17430539

DOI: 10.5281/zenodo.17430539

Soils for Europe

Outlook on the knowledge gaps to reduce soil erosion

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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 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.

DOI: 10.5281/zenodo.17430539

- 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 exac-

DOI: 10.5281/zenodo.17430539

erbating 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.

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)

Figure 1. Social, economic and environmental impacts of soil erosion.

DOI: 10.5281/zenodo.17430539

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 identified through a prioritization exercise conducted over the past few months by SOLO partners and participants in the Think Tank activities across all 10 Think Tanks supported by the project.

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.

DOI: 10.5281/zenodo.17430539

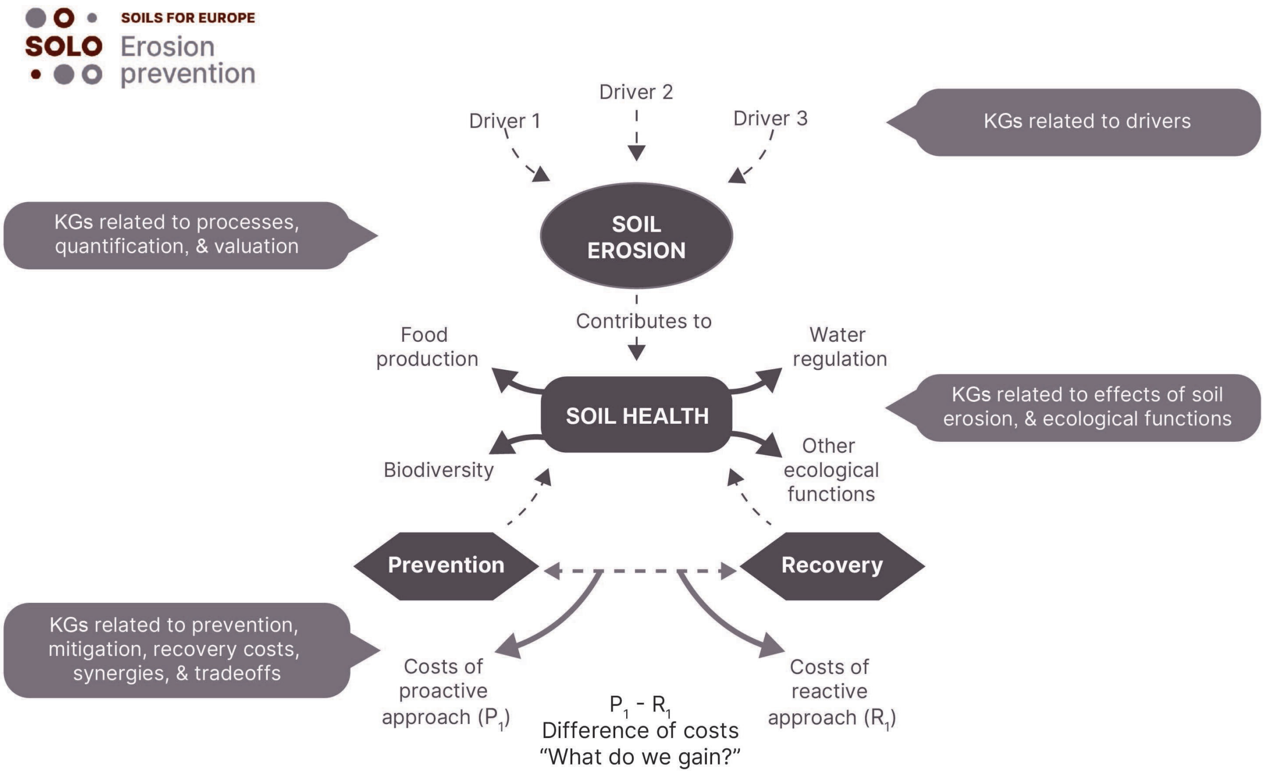

Figure 2. Think Tank's approach to the identification of Knowledge Gaps (developed by the authors).

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

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

DOI: 10.5281/zenodo.17430539

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.

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 is 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) also 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

DOI: 10.5281/zenodo.17430539

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,

DOI: 10.5281/zenodo.17430539

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, hin-

DOI: 10.5281/zenodo.17430539

dering 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

DOI: 10.5281/zenodo.17430539

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-be-

DOI: 10.5281/zenodo.17430539

ing. 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

DOI: 10.5281/zenodo.17430539

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).

DOI: 10.5281/zenodo.17430539

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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Outlook on the knowledge gaps to improve soil structure

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1. Introduction

Soil is healthy when it is in good chemical, biological and physical condition and can continuously provide as many ecosystem services (such as safe, nutritious and sufficient food, biomass, clean water, nutrients cycling, carbon storage and a habitat for biodiversity) as possible (European Environment Agency 2023). Soil structure contributes to all soil functions that underpin ecosystem services (Fig. 1). Water regulation, purification, and habitat provision are crucial for maintaining nutrient cycling, as well as disease and pest suppression, which in turn support soil productivity and its role in climate regulation (Schulte et al. 2014). Therefore, disturbances to natural soil structure impact ecosystem functioning. However, the relative importance of these different ecosystem services provided by soil structure in different pedoclimatic zones, soil types and land-use types may vary. Also, the info on the importance of protecting soil structure and on the best management practices needs to reach the diverse group of relevant actors from land owners to decision makers.

Soil structure really makes soil what it is and is vital for functioning of soil. Soil can exhibit a single-grained structure in which separate mineral particles are not aggregated but are only loosely packed like in sand dunes. Soils can also exhibit massive structural condition in which separate soil particles are bound together by cohesive forces. Massive structure can be found deep in soil profiles in a fine textured soil. However, in most soils, there is some type of aggregation where mineral particles are forming clusters as a result of drying and wetting cycles, chemical ponding and biological activity. The aggregate structure promotes soil health by allowing water infiltration, aeration, root growth, and nutrient cycling as well as by providing niches for various soil organisms. In organic soils, that are formed through the accumulation of partially decomposed plant biomass in fens and bogs, the structure is defined by the peatland vegetation and the degree of the decomposition (Rezanezhad et al. 2016).

Soil structure has been defined as the "spatial arrangement of solids and pores at scales smaller than the soil horizon and consists of clusters of solids and pores called aggregates, that have hierarchical, emergent properties, and memory that define their functions" (Yudina and Kuzyakov 2023). Some of the pores should also be continuous and large enough enable preferential flows and rapid infiltration. The arrangement of the particles, aggregates, and voids determine the capacity of soil to transmit solutes (water and nutrients) and gases (oxygen, carbon dioxode, methane, hydrogen) through the soil volume, and to retain and provide water substances such as nutrients to plants and soil biota. Important is also the significance of aggregate size variation in soil formation and its relationship with microbial communities and soil functionality like water and gas flows for rooting. See vocabulary for soil structure in Table 1.

Good soil structure helps to resist soil erosion and compaction, which can degrade soil quality (Rabot et al. 2018) (Fig. 1). Thus, the structural quality of soils can be defined according to their resilience to climatic disturbances, such as varying weather conditions, field traffic/forest machinery and/or management practices such as tillage. European Environment Agency (2023) has listed soil processes than can potentially weaken the soil status. Soil compaction and erosion are indicated as important processes that weaken soil quality, and they are tightly linked to soil structure. While human interventions like artificial drainage can enhance biomass production in wet conditions, practices such as intensive tillage and the use of heavy machinery can destroy soil aggregate structure and cause compaction, compromising the soil's ability to store and purify water. A good soil structure is an optimal balance between water retention and hydraulic conductivity and to gas exchange in soil.

Soil erosion and, elemental leaching, as well as resilience to drought periods, are linked to soil structure determining e.g. soil moisture conditions (Luk 1985, Dorman et al. 2015, Wei et al. 2007). Knowledge of the soil structure is in key

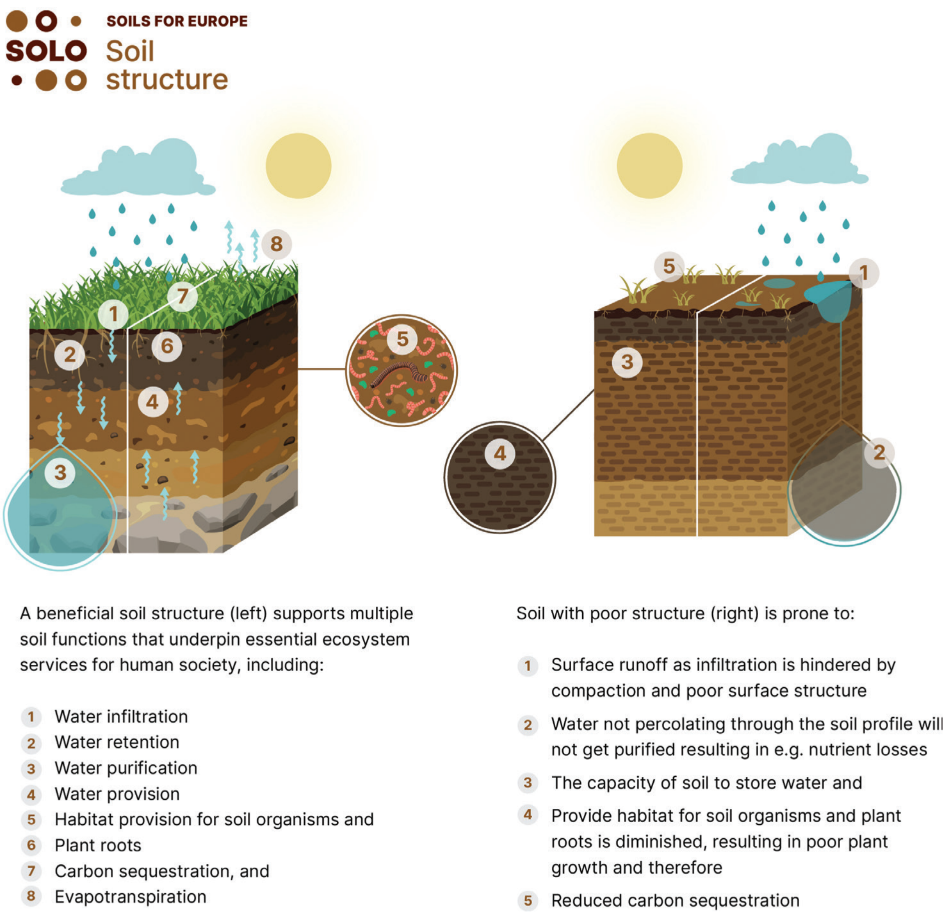

Figure 1. A beneficial soil structure (left) supports multiple soil functions that underpin essential ecosystem services for human society. The problems that are occurring within the EU and globally are illustrated on the right-hand side.

DOI: 10.5281/zenodo.17430539

Table 1. Vocabulary related to soil structure.

Term	Explanation
Water retention	Soil's ability to store water. With a smaller suction (<100 kPa) the amount of water retained depends mainly on the capillary effect and pro-size distrubution, with larger suctions mainly on the soil texture and specific surface of the soil
SOM	Soil organic matter, soil solids that consists of plant or animal tissue in various stages decomposition
Soil structure	Spatial arrangement of solids (clay, silt and sand sized particles) and pores in a volume of soil
Pore space	Volume of the space between the solid particles in the soil
Pore size	Size of a pore described usually by the diameter
Pore space	Continuity of pores (% of total porosity V/V) - essential for saturated hydraulic conductivity to ensure infiltration under flooded conditions
Wilting point	The minimum amount of water in the soil that the plant requires not to wilt. Below the wilting point, water is held so tightly in the soil matrix that it cannot be taken by the plants
Field capacity	The amount of water retained in the soil after excess water has drained due to gravity
Particle size distribution	Shares of different sized particles in a mass of soil
Bulk density	Measure of the mass of soil in a given volume, often expressed in grams per cubic centimerer (g/cm^3)
Macro pores	Macropores are large soil pores, typically Ø greater than 30µm, which allow for the rapid movement of water and air through the soi. (incl. pore shape - look above)
Micropores	Small soil pores, typically Ø smaller than 30µm, water moves mainly by diffusion and by plant uptake
Organic soil	Soil formed through the accumulation of partially decomposed organic biomass (Metsämaa- Forest soils Glossary 2024)
Mineral soil	Inorganic soil, loose inorganic matter formed from the bedrock as a result of geological processes
Growth factor	Any internal or external element that influences the growth, development, or reproduction of a plant

role when estimating soils' ability to store and conduct water as well as their water infiltration capacity (Burger and Kelting 1999, Schoenholtz et al. 2000Drobnik et al. 2018). Water retention is responsible for life on Earth as we know it. It allows for a huge air-water interface which permits aquatic aerobic activity to proceed under a range of environmental conditions.

Soil structure and related moisture conditions control biogeochemical processes essential e.g. to timber (Henttonen et al. 2014) and food productivity. Optimal soil structure supports primary production through water retention and habitat provision for biota that contributes to nutrient cycling, and pest and disease control.

2. State-of-the-Art

2.1. Current state of the knowledge on Soil Structure

Soil structure dictates the hydraulic properties of soil and is dependent on the soil properties such as organic matter content, texture including clay minerals or stones, and compactness of the particle arrangements. Bulk density is often seen as a indicator of the soil structure, but it is texture depended and does not indicate the pore size distribution (Wösten et al. 2001, Van Looy et al. 2017, Launiainen et al. 2022). Water retention characteristics (WRC) and hydraulic conductivity can be determined by direct in-situ or laboratory measurements or estimated using pedo-transfer functions (PTFs) based on the soil data (Wösten et al. 2001, Van Looy et al. 2017). Important parameters to be measured for soils from the point of view of soil hydraulic properties are e.g. total porosity (TP) and the water content of the soil at field capacity (FC) which is the amount of water stored in soil against drainage (Cools and Vos 2020, Launiainen et al. 2022). For plant available water, the wilting point (WP) is a crucial parameter especially in dry conditions (Cools and Vos 2020, Launiainen et al. 2022). The available water capacity (AWC) is the plant available water between FC and WP (Launiainen et al. 2022). Knowledge about these parameters forms a basis for estimating the effect of soil structure on soil hydrological conditions.

In many cases there are knowledge gaps in data on water retention characteristics (WRC) of soils (Launiainen et al. 2022). According to Launiainen et al. (Launiainen et al. (2022) hydrological, biogeochemical and forest models require data on WRC to perform improved hydrological

DOI: 10.5281/zenodo.17430539

predictions for forest soils. Similarly, understanding a soil's susceptibility to compaction and to characterize soil mechanical properties as a function of soil moisture requires more data of the compressive behavior of the different soil types in different moisture conditions (Torres et al. 2024).

Intensification of land management, especially soil tillage, is a key driver of soil structural deterioration (Keller et al. 2019, Klöffel et al. 2024). Increasing weight of the machinery used in agriculture and in forestry poses a threat to soil pore system through compaction causing changes in pore volume, pore-size distribution, and connectivity. In addition, heavy machinery can compact deep soil layers and then recovery can take longer than compaction in surface layers (Berisso et al. 2012). From a biological perspective, the pore network is highly pertinent as it is the habitable space for microbial species and compaction affects directly to the habitat of soil biota (Longepierre et al. 2021). Report of the Finnish Ministry of Environment (Haavisto 2023) indicated also that soil compaction was one of the most important processes that can weaken soil status. However, in Finland, while there are individual scientific studies on soil compaction in agricultural, forest, and urban soils, large-scale monitoring at the mapping level is lacking. This means that there are knowledge gaps in soil compaction information at nation-wide level (Haavisto 2023). This is probably the case also in many other countries.

Mechanisation of agriculture has enabled intensive tillage which is related to reduced aggregate stability and increased risk for surface sealing and erosion (Bronick and Lal 2005). These management-induced changes in soil pore system affect water and gas movement in soil (e.g. Strömgren et al. 2016) and therefore, also the living environment of soil biota and plant roots (Oades 1993). When changes in aggregate stability and pore system lead to reduced soil productivity, soil biodiversity, the input of carbon (C) through decaying plant materials as well as exudates and debris of soil biota (Costa et al. 2018) as well as soil necromass is also reduced leading to decreasing organic carbon (OC) content in soil. Lower SOC content is related to lower aggregate stability (Six et al. 2000, Soinne et al. 2016) thus enhancing further the risk for structural deterioration.

The growing interest on reduced tillage and carbon farming have potential to improve aggregate structure but improving the growth conditions of roots and enabling proper water and gas movement deeper in the soil would require loosening the soil structure at least down to the desired root penetration depth. No-till management known to improve soil aggregate stability may, depending on climate and soi type, enhance soil compaction and therefore slowly lead to lower productivity. On the other hand, reduced disturbance of soil improves the living conditions of soil organ isms and therefore may have positive effect on soil porosity and macroporosity.

Similarly, as in agriculture, forest management practices (timber extraction, land preparation by terraces, and so on) affect soil structural properties. Different management practices also bring along forest floor vegetation changes mediating the effects of drought on soil. One example are the forest fires in Portugal which are a major threat affecting soil structure, soil biota, soil physicochemical properties with also off-site effects (flooding, ash deposition in damns, etc.).

In addition to soil management, climate change puts the soil structure on stress through extreme weather conditions. Extreme rain events lead also to changes in pore structure which maintains the healthy soil. Drought can cause irreversible or reversible shrinkage of soil leading to preferential flow paths for water solutions. Drought has also been shown to decrease carbon accumulation to soils and the forest stand age and management can affect the resilience and response of soil to drought and heat waves. We do not know what happens to soil structure when these extreme weather events follow each other repeatedly. There should be critical analysis of some emergency measures currently adopted in the post-forest fire phase, such as emergency stabilization or aerial seeding. The advancing climate change can lead to continuous change in soil structure, and we need more information on ecosystems that undergo change such as thawing permafrost.

While we can destroy soil structure with, for example intensive and wrongly- timed soil tillage and forest management practices and excessive handling of soil (Fig. 2), but we can also preserve

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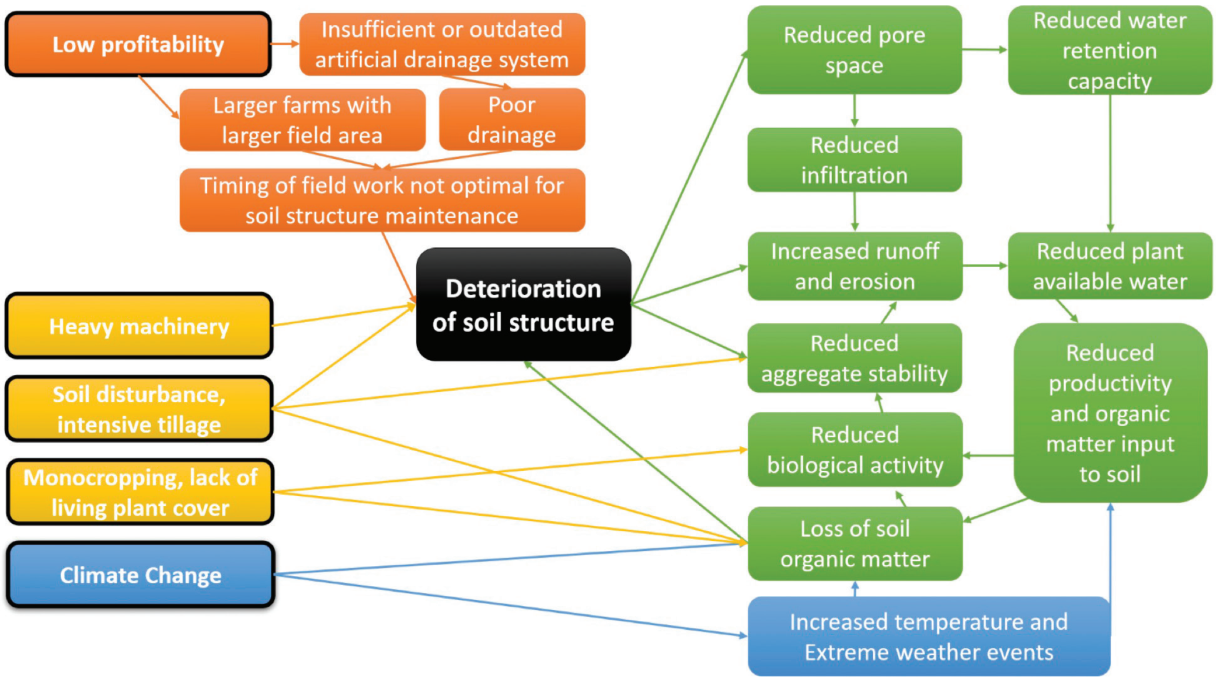

Figure 2. Drivers (black borders) affecting structure of agricultural soils include factors such as overall policies and economic situation (orange), soil management practices (yellow), and environmental factors (blue). Structural deterioration can impair soil functioning and create a vicious cycle of further soil weakening.

soil structure. Regenerative agriculture practices (e.g holistic grazing, catch crop, cover crop and crop rotation among others) provide an option for the intensive management practices. But can we improve/regenerate destroyed structure of arable mineral soil? Or will the structure and functioning of restored peat soil be equivalent to the unmanaged peat areas?

2.2 Prioritization of knowledge gaps

Methodology

The methodology used followed the SOLO Think Thank methods and is described in Fig. 3. We started with desk research by Think Thank leaders and members and continuedwith stakeholders through multiple approaches. Prioritisation of the 10 key knowledge gaps took place in an online meeting with stakeholders and scientist and in Bulgaria by key stakeholders. Voting was conducted in Bulgaria, online and for soil structure Think Tank we organized a separate voting during the Finnish Soil Sciences days. Each stakeholder could vote for the three most important knowledge gap or request some of them to be combined. Intriguingly, in the online meeting and during the Soil Sciences days, the same top three were formed.

A list of the top 10 identified knowledge gaps can be found in Table 2.

3. Roadmap for Soil Structure

3.1 Key knowledge gaps

1. How can we manage and adapt soil structure to support effective water regulation and habitat provision across scales—from microhabitats to catchment areas—in the face of climate change and evolving land-use practices?

The change in management or caused by natural disturbances may lead to new structural state in soil or the change may be short-lived and there will be a reversion to the pre-disturbance state. The consequences of these changes in land management or changes resulting from natural disturbances, and the rates of these changes

DOI: 10.5281/zenodo.17430539

Table 2. Ranking of the top 10 knowledge gaps identified (a full list of all identified knowledge gaps is given in section 3.3).

Rank	Knowledge gap	Type of knowledge gap
1	How can we manage and adapt soil structure to support effective water regulation and habitat provision across scales - from microhabitats to catchment areas - in the face of climate change and evolving lang-use practices?	Knowledge development gap, Knowledge application gap
2	How can we quantify and value soil structure to support sustainable land management, economic assessments, and predictive modeling across scales and applications?	Knowledge development gap
3	How do biological, physical, and chemical factors in soil interact to build and maintain its structure, and how can management practices harness these interactions to enhance soil structural resilience or restore it after deterioration?	Knowlegde development gap, Knowledge application gap
4	How do forest management (timber extraction, soil preparation) and other disturbances (forest fires) effect soil structure and what are the off-site effects (e.g. flooding)?	Knowledge development gap
5	Impact of circular economy and soil improvement materials in maintaining or improving soil structure in changing environment	Knowledge development gap
6	How is a changing climate and operational/business environment challenging current management practices, and what impact will it have on soil structure if these practices are maintained or adjusted to the changing environment?	Knowledge development gap, Knowledge application gap
7	How can weto increase the interest towards soil structure and knowledge on the role of soil structure (especially sub soil) on water management among the lang- managers? How can weto help farmers and land managers to avoid management-induced soil structure?	Knowledge application gap
8	How much the soil has compacted is the soil, and can the soil recover from compaction? Soil sealing and the effect on soil structure, can the soil recover from sealing?	Knowledge development gap
9	Supply chain pressure: How do weto get better contracts for the farmers so that the contracts don't put themyou in field at the wrong time?	Knowledge application gap
10	Does soil classification based on soil texture lose the information needed for soil structure management?	Knowledge development gap

may differ depending on climate, soil type a nd vegetation cover, management, and disturbance history. For example, the use of heavy machinery may lead to soil compaction affecting soil functions like water flow, regulation and retention, soil aeration, habitat provision and therefore ability of soil to provide ecosystem services such as primary production. Compaction and reduced plant growth can lead to increased runoff of nutrients and carbon, and reduced drought tolerance. Compaction may cause problems for soil organisms and their function (Meurer et al. 2020) decreasing their biological activity and leading to lower decomposition of soil organic matter and disturbing the maintenance of soil structure due to reduction of exopolysaccharides, glomalin and fungal hyphae. Therefore, more information is needed on specific management practices in different climatic environments and soil types that consider the land-use and functioning of the soil for provision of as many as possible ecosystem services.

Changing intensity of weather events resulting from climate change can cause problematic soil structural changes that need to be examined more. With changes in weather events and in annual timing of them, there is a transition in timing of the soil management practices at both forest soils, agricultural soils and in the urban areas. When the soil is too moist, certain machinery cannot be used without causing dramatic effects to the soil structure. Proper winter in Northern Europe with frost period protects soils from damage and allows use of heavy machinery (e.g. in forests). In addition, frost and freeze-thaw cycles are reported to improve soil structure in arable lands by fragmenting large soil clods and therefore enhancing consolidation of beneficial seedbed (Leuther and Schlüter 2021). However, the reported effects of multiple freeze-thaw cycles on aggregate stability vary, with studies reporting both increased and decreased aggregate stability (Lehrsch 1998, Kværnø and Øygarden 2006, LI and FAN 2014, Wang et al. 2012). Unfortunately, currently climate change appears as milder temperature and increased precipitation in winter period, leading to greater moisture content and leaching of mineral and organic material from the soils (greater erosion) (Kværnø and Øygarden 2006). In addition, the possibility for increased leaching is not restricted only to mineral and organic matter but may concern also particulate material (suspended solids) as well as nutrients essential for

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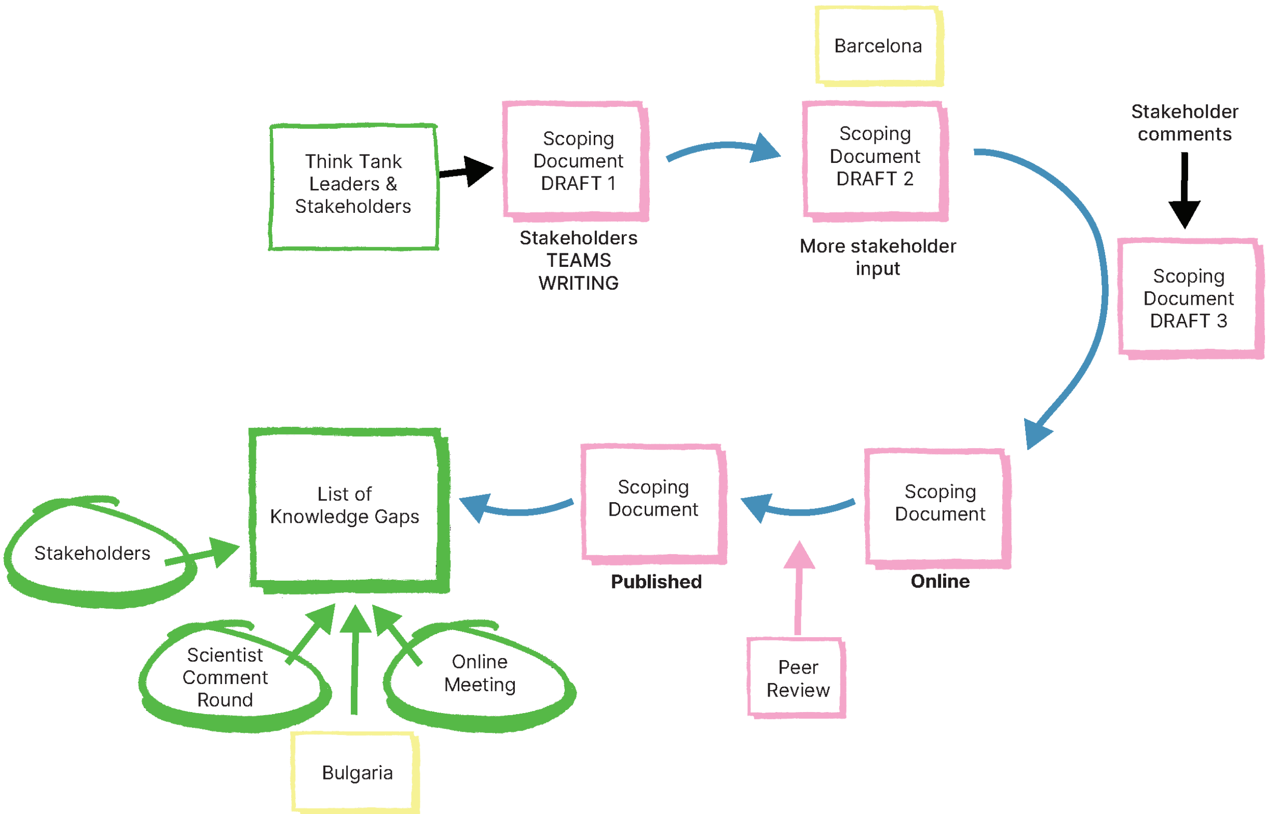

Figure 3. Methodology of soil structure Think Tank.

e.g. forest ecosystems in the long run (Machado et al. 2018). Increased occurrence of heavy rain is possible also in more Southern regions, and thereby the concern of the loss of soil organic matter and soil structural changes is global. Abnormal weather events make trees susceptible to forest diseases, and in turn, loss of trees alters soil stability. The impact of extreme weather events on soil structure can vary by soil type, potentially leading to either improvement or degradation. It is essential to develop management strategies that account for both extreme rainfall and extreme drought. This could include novel thinking in crop rotations and plant breeding to enhance possibilities for green plant cover throughout the year.

Soil operations affect the soil structure, but with optimal timing the destabilising effect can be reduced. For example, soil wetness and inherent soil properties contribute to soil structural vulnerability and their interaction is complicated depending also on the management practices (Hu et al. 2023). Also grazing and compaction by animals can be severe (Pietola et al. 2005). Minimum tillage has been considered the best approach from numerous biological points of views such as symbiotic fungi and arthropods, although this might not necessarily be the case with increasing number of weeds and reduction in yield levels. Furthermore, omitting tillage have been reported to result in enrichment of nutrients like phosphorus in the uppermost surface layer (Jarvie et al. 2017, Uusitalo et al. 2018). This will lead to increased risk of loss of dissolved phosphorus into surface water increasing eutrophication (Jarvie et al. 2017, Uusitalo et al. 2018). Additionally, if soil water management like drainage is not functioning properly in clay soils, the aggregates loose stability under water saturated conditions. Therefore, we need information on soil specific management options in different climatic conditions and land- use systems to improve the functionality of soil structure.

On forest land there is a growing interest among landowners towards continuous cover forestry, where one avoids clear-cuts, or site

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preparations for the planted trees are targeted for one seedling separately to avoid overall soil tillage. If continuous cover forestry practices get more common in organic soils where it is more applicable than in mineral soils, and this may result in a significant change by reducing the need for soil preparation and for maintenance ditches on drained peatlands. Different harvesting practices may also have a variable effect on the forest soil structure and nutrient amounts remaining in the site after cuttings. If cutting includes all tree compartments (whole tree harvesting), this increases the loss of organic matter and nutrients compared to that remaining in the soil in stem-only harvesting. The distribution of logging residue piles on the site may also affect soil structure (physical properties) and nutrition (organic matter, chemical properties), i.e. if the logging residues are located only on restricted parts in the harvested area due to modern harvesting techniques. In addition to physical soil management, human induced land use also includes change in plant species, particularly in agriculture but to certain extent also in forest systems. The narrowing of plant species selection has further extended to genetic diversity via the use of breeding of plant material often to maximize productivity. Plant breeding has changed root exudates, root microbes, soil chemistry via microbes, lack of arbuscular mycorrhiza, glomalins and other extracellular polymeric substances (EPS) thus affecting the soil structure.

The emerging issue of microplastics in European soils is conceptually also a physical contaminant and affects soil aggregation and pore-size distribution (Han et al. 2024, Wang et al. 2023). However, the impact is likely to fluctuate based on the textural composition of the soil, as well as the size, shape, and aging characteristics of the microplastics particles (Lehmann et al. 2021, Wang et al. 2022).

The improvement of soil structural quality resulting from changes in soil management can be assessed by physical-structural-hydrological parameters (aggregate stability, MWD, pF-curves, bulk density, Ksat values) and methods linked to soil microbiology. A particular challenge is that, in many cases, soil in poor condition is not very responsive to management practices.

2. How can we quantify and value soil structure to support sustainable land management, economic assessments, and predictive modeling across scales and applications?

Good soil structure is characteriszed by an arrangement of particles that facilitates the movement of water and air, while also providing stability to resist erosion and compaction. However, soil pore space (total pore volume and pore size distribution) varies greatly depending on soil particle size distribution and thus, the optimal structure or pore-size distribution that can be obtained or maintained varies depending on soil type. Also, land-use and location of the soil sets different expectations for soil structural functioning. In a cool humid climate, it is essential to get the excess water drained from the fields in the spring to get the growing season started whereas in the catchment scale, it is important to maintain areas that can hold the draining water to level of the flood peaks. Therefore, the evaluation of the goodness of soil structure should be done considering the ecosystem services that are expected the soil to produce within the land-use and the capacity of the specific soil type.

Soil aggregates are considered for hot spots for biological activity and biogeochemical processes and are of high importance defining soil structure and pore space. However, the efficacy of aggregate research in elucidating functioning of soil structure has come under scrutiny. Sampling aggregates has required disrupting the surrounding soil environment, raising concerns that aggregates may partially result from the sampling procedure, thus potentially compromising their representativeness (Young et al. 2001, Garland et al. 2023). Furthermore, non-destructive imaging techniques have failed to detect aggregates in undisturbed soils or in deeper soil layers (Garland et al. 2023). Recently, Garland et al. (2023) concluded that aggregates can be separate units but taking into account the processes contributing to the formation and turnover of aggregates, they do not need to have distinct physical boundaries. I n fact, tillage- produced aggregates are often loosely packed and form inter-fragment spaces whereas natural aggregates are more likely to be seamlessly em-

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bedded in the surrounding soil matrix (Or et al. 2021). Yudina and Kuzyakov (2023) stated that they “consider the pores and the interfaces as the arena of the physico-chemical and biological processes, but aggregates as the result of these processes“. Consequently, aggregates are the core concept of stable pedogenic features (soil memory) and allow the realization of a thermodynamic view on the soil structure. This further highlights the importance of understanding aggregation and developing methods to study aggregates in their functional surrounding.

How to measure soil structural functioning at relevant scales? Assessing the soil structure holds a great variety of analysis methods. Soil compaction can be for example estimated by determining precompression stress, penetration resistance, soil organic matter as well as hydraulic conductivity and plant available water capacity (European Environment Agency 2023). Different methods emphasize different aspects of soil structure, and some may be suitable for only certain kind of soils. Some methods are cheap and widely applicable in context with the field sampling and utili szed for example in the current European-wide field studies and surveys, but less informative and difficult to be interpreted. For example, soil bulk density (BD) is widely measured property used to describe soil structure. However, interpreting BD results from soils with various mineral composition of particle size distribution is difficult. Furthermore, BD is a static measure lacking the link to soil functioning and information for example on pore connectivity. On the other hand, certain newer methods, such as X-ray computed tomography (CT), allows visualization and quantitative analysis of the interior of porous structures (Haubitz et al. 1988) and provide in depth information e.g. on soil pore connectivity through quantitative image analysis tools (Koestel 2017), but are expensive and need rare equipment.

Further, soil structure contributes to ecosystem services in different scales (micron, pedon, catchment), and upscaling the information from small sized samples (Ø 5 – 10 cm) is challenging taking into account the large heterogeneity of soil structure in space (Vereecken et al. 2019). On the other hand, collection of large number of samples would not be feasible. So far, a satisfactory way to measure soil structure non-invasively and at relevant field scales has not been available (Romero-Ruiz et al. 2018). Therefore, effort is needed to make best out of new and rapidly developing technologies (e.g., satellite data, AI, digitalization, imaging, etc.) to combine soil structure related measurements at different levels. Combination of new technologies such as nanoscale geophysics, tomography, spectrometry, or single cell genomics (Hartmann and Six 2022, Romero-Ruiz et al. 2018) to Sentinel or other satellite derived data are probably needed to bridge the still existing knowledge gaps between soil management and structural features such as pore structure, connectivity, and soil functioning. Furthermore, it is crucial to develop methods for continuous measurements that capture the short-term changes in soil when not at equilibrium state (in contrast to current laboratory measurements).

Soil structural characteristics are currently not properly accounted in global hydrological and climatic models largely due to the methodological constrains (Launiainen et al. 2022, Vereecken et al. 2022), although recent efforts in model development have been promising (Jarvis et al. 2024). Efforts put on developing methods for measuring functioning of soil structure in different scales support the large scale hydrological and hydromechanical modeling (Fatichi et al. 2020). Better hydrological models will help to estimate the impact of structural quality on soil functioning and in ecosystem service provision considering the changes in agricultural management and climate in the future (Jarvis et al. 2024). This can help in estimating the economic value of the properly functioning soil structure and therefore provide motivation and resources to enhance soil structure improvements.

3. How do biological, physical, and chemical factors in soil interact to build and maintain its structure, and how can management practices harness these interactions to enhance soil structural resilience or restore it after deterioration?

Soil microorganisms play a key role in the formation of soil structure and its dynamics. In addition to bacteria and soil microfauna, particularly fungi are shown to be involved in the formation and

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stabilization of soil aggregates, also at the macroaggregate scale (Lehmann et al. 2020). Soil aggregating capability of fungi is hypothesized to be due to their physical, morphological, chemical and biotic traits. Fungal diversity in soils is high, and also large differences among fungal species are found in their ability to aggregate soil (Lehmann et al. 2020). Furthermore, recent experiments indicate that by fungal inoculation, soil hydraulic properties and aggregation can be improved by connecting soil particles via hyphae and modifying soil aggregate sorptivity (Angulo et al. 2024). The effect varied according to the fungal strains and soil moisture levels.

Soil aggregate stability is often used as an indicator of soil structure (Six et al. 2000) and reflects soil's ability to stand erosive forces. Soil aggregates are associates of organo- mineral particles bound together with forces that are stronger than the forces between adjacent soil aggregates; biologically synthesised extracellular polymeric substances (EPS). EPS are composed mainly of polysaccharides, proteins and DNA excreted by soil microorganisms. EPSxtracellular polymeric substances are also responsible for the cohesion of microorganisms and adhesion of biofilms to surfaces, they affect soil spatial organization and enable interactions among microorganisms (Costa et al. 2018). The cementing agents that enhance aggregate formation are well-known and natural aggregates are formed as a result of biological activity resulting in stabilization by biopolymers, and mineral particle enmeshing by hyphae and roots. Small and fine roots produce optimal conditions to form and to stabilisze aggregates due to the polysaccharides produced by the microorganisms (Hallett et al. 2022). Furthermore, the roots maintain separation between the aggregates.

In agriculture, tillage produces soil fragments similar to biologically formed aggregates, but the stability of the fragments against mechanical disturbance and wetting is lower (Or et al. 2021). More information is needed on how these differently formed aggregates impact the functioning of arable and natural soils and on the relative importance of these different types of aggregates in preserving soil organic carbon stocks in different soil types and under different land-use and management. Small- sized aggregates seem to improve soil hydrological properties like water retention capacity and infiltration, so the estimation of this fraction or derived indexes or ratios, which relate the percentage of micro to macroaggregates, can give an interesting information about the condition and degradation of Mediterranean soils.

The fundamentally important interactions between chemical and biological factors in maintenance of soil structure provide a clear potential introducing new possibilities for soil management, also in the context of climate change. We agree that the first step is to identify the most important key organisms supporting soil structure. However, rather than direct cultivation, understanding the ecology of the key microorganisms would provide more efficient long-lasting impact. Supporting ecosystem of the key organisms, such as suitable carbon support via host plant or interacting helper microbes would be way to soil structure improvements via use of soil biota.

Indeed, biological processes influencing soil structure are not happening only microbial but rather in plant root-microbe interphase. Roots and attached microbiota improve nutrient cycling, stabilization of soil against erosion, water balance of soils and even soil carbon storages (Hallett et al. 2022) as well as may mitigate soil compaction damages (Jin et al. 2017). Abundant use of fertilizers decrease the benefit of root–soil interface in nutrient uptake, and modern crop cultivars may have smaller root systems. These may lead to lowered amount of rhizodeposition and eventually impact on soil properties. Plant breeding is suggested to be a potential future tool in harnessing the root-soil interphase to build and preserve soil structure and sustainability (Hallett et al. 2022). Another interesting suggestion is that, as ethylene has been found to act as an early warning signal for roots to avoid compacted soils, this could provide a pathway for how breeders might select crops resilient to soil compaction Pandey et al. (2021).

We need information, not just on agricultural soils, but on the physico-chemical processes, all the biological processes and interactions, from

DOI: 10.5281/zenodo.17430539

larger plants and animals to fungal hyphae and tiny microbes. How soil organisms interact with each other and with the abiotic environment affects soil structure. The role of soil invertebrates in crop production has received relatively little attention. The biotic part maintains the structure, how is it affected by climate change and changes in the soil habitat? How do soil animals and microbes respond to extreme events?

Recovery of soil after disturbances is tightly linked to soil structure. We do not know how long it takes for soil to recover nor how we should measure soil recovery. The anthropogenic effects have a major role in shaping soil structure, but we do not have a complete and soil- and climate-specific understanding on their direct impacts on soil structure and how to retain sustainability of soil after disturbance. The potentially important role of plants in restoration needs also more soil and management specific understanding. Furthermore, as the functioning of soil results from an interplay of soil structure and activity of soil organisms, recovery of the vast areas of deteriorated soils on earth is a challenge.

3.2 Prioritized knowledge gaps

4. How does forest management (timber extraction, soil preparation) and other disturbances (forest fires) affect soil structure and what are the off-site effects (e.g. flooding)?

Timber extraction is performed in forests nowadays often using machinery which may cause in some cases soil compaction. After clearcut, it is typical to perform soil preparation in order to improve soil structure and properties for tree growth of the next tree generation. There is a need for more information on how soil preparation actions affect soil structure in a long run (e.g. SOC development, mineral weathering) and nutrient leaching. Forest fires impact soil organic matter, clay mineral structure, and can significantly alter the soil pore system (Agbeshie et al. 2022), thereby affecting overall soil functioning. Therefore, the risk and frequency of forest fire occurrence should be assessed, and their potential impacts on soil functioning carefully evaluated.

5. Impact of circular economy and soil improvement materials in maintaining or improving soil structure in changing environment

Agricultural use of organic amendments derived from the pulp and paper industry have generally shown positive impacts on soil physical properties such as soil aggregation. Sludge addition has also reduced particle and phosphorus losses from soil to percolation water, indicating potential for erosion mitigation (Rasa et al. 2020). However, when enhancing circular economy, the quality of the materials in question should be carefully investigated in the light of soil functioning since side streams may contain harmful substances that impair for example soil structure stability and functioning. Therefore, more information is needed on the impacts of different side streams on soil structure in different soil types and climate conditions.

6. How is a changing climate and operational/ business environment challenging current management practices, and what impact will it have on soil structure if these practices are maintained or adjusted to the changing environment?

Poor profitability of agriculture may impair the investments needed for adjusting production to maintain soil structure in changing climate. Furthermore, changing diets change the crop rotations and quality of organic matter input into the soil. Also new crops may require new type of machinery which should be evaluated in the light of changing climate.

7. How to increase the interest towards soil structure and knowledge on the role of soil structure (especially sub soil) on water management among the land- managers?

Among farmers, nutrient inputs have gained a lot of attention, and this may originate from the fertilisszer industry being a large business. However, soil structure is as important growth factor

DOI: 10.5281/zenodo.17430539

as poor structure may significantly prevent the plants from utilizing the nutrient input given in fertiliszers. Therefore, knowledge on soil structure and how to manage the structure of different soil types is crucial information to improve or maintain soil productivity as well as to reduce environmental impacts of food production.

8. How much the soil has compacted and can the soil recover from compaction? Soil sealing and the effect on soil structure, can the soil recover from sealing?

Plant roots are able to modify soil structure via numerous mechanisms, for example pore formation (Jin et al. 2017). Thus, when aiming to recover soils after compaction, in addition to management, increase in root growth may improve plant resource accessibility, and thereby also crop productivity. Increased root growth has also long-term effects on compacted soil via organic matter feed. The root penetrability and growth could be improved through plant breeding (Colombi and Keller 2019, Hallett et al. 2022). In forest soils, the key issue is in avoiding compaction by operational planning of forest management, such as which forest units to be cut in which season and which machine resources to be used (Labelle et al. 2022). Operations eg. usage of mulch to accelerate the recovery of soil properties, or even mechanical site preparation, could be used for loosening the topsoil.

9. Supply chain pressure: How to get better contracts for the farmers so that the contracts don't put you in the field at the wrong time?

Farmers' contracts with traders can be very binding and require delivery of products at the exact time agreed. However, the ripening of the harvest and the farming practices are highly dependent on weather conditions. Excessively tight contracts can force farmers to harvest under conditions where soil strength is too low, for example, due to excessive wetness. In this case, adherence to the contract will lead to a deterioration of the soil structure and may risk future yields. On the other hand, breach of contract often results in significant financial losses for the farmer. Increasing awareness and understanding of the importance of soil structure for soil function and yield potential could help to increase flexibility in contracts. Furthermore, the flexibility of contracts between farmers and traders should be enhanced, especially for crops that are more vulnerable to weather variability.

10. Does soil classification based on soil texture lose the information needed for soil structure management?

For agricultural purposes and within farmers and advisory services, soils are often classified according to their texture (particle-size distribution). However, the proportion share of clay, silt and sand does not reveal soil characteristics related to parent material, climate, relief or resulting from the age of the soil (soil forming factors). Classification systems like World Reference Base which consider the diagnostic characteristics and their relationship with soil-forming processes can better reveal conditions in soil related to soil wetness or properties originating from the quality of the parent material (Gray et al. 2011). People responsible for soil management decisions should be better informed about the role of soil-forming and soil health related factors in shaping soil characteristics across different climates and topographical locations.

3.3. Overview

An overview of the knowledge gaps can be found under Suppl. material 1

Acknowledgements

We wish to acknowledge our Think Tank members, especially Seija Virtanen, Nanois Nunan, Liisa Pietola, Laura Höijer and Pedro Monteiro.

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Outlook on the knowledge gaps the EU global footprint on soils

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Introduction

This Think Tank (TT) focuses on Specific Objective 7 (SO7) of the European 'EU Soil Mission: A Soil Deal for Europe' (hereafter Soil Mission), that relates to reducing the EU global footprint on soils. Within this specific Soil Mission objective, two main targets are defined in the Soil Mission Implementation Plan:

- T 7.1: Establish the EU's global soil footprint in line with international standards.
- T7.2: The impact of EU's food, timber and biomass imports on land degradation elsewhere is significantly reduced without creating trade-offs.

These objectives have to be in line with the Zero Pollution Action Plan. This implies that air, water and soil pollution will have to be reduced to levels no longer considered harmful to health and natural ecosystems, that respect the boundaries with which our planet can cope, thereby creating a toxic-free environment, by 2050. The main objective of this document is to highlight actionable knowledge gaps and research themes, that are critical to achieve to attain the SO7 specific objectives.

Background to the international dimension (as presented in the Soil Mission Implementation Plan)

SO7 adds an international dimension to the EU Soil Mission, which is, in its other objectives, primarily focused on improving soil health and soil functioning in the European Union. As stated in the Mission Implementation Plan, soil health is crucial for three UN conventions (UNCBD, UNCCD, UNFCCC), as well as for the Sustainable Development Goals (SDGs), and is an issue of worldwide concern. To avoid negative impacts of EU actions on soils outside the EU (mostly in terms of consumer demands), the Soil Mission acknowledges the need for global alignment of the soil health concept and actions to reduce the soil footprint outside the EU from imports of food, biomass, and timber. This focus on biomass has been questioned by multiple stakeholders, as highlighted in the initial knowledge gaps. The Soil Mission Implementation Plan emphasizes that the beyond-EU dimension can and should leverage existing partnerships.

For Africa, the Food and Nutrition Security and Sustainable Agriculture (FNSSA) partnership, part of the African Union-European Union High-Level Policy Dialogue (HLPD), is indicated as a potential starting point. It focuses on soil health for sustainable food systems. The related Horizon 2020 projects Soils4Africa and LEAP4FNSSA have invested first efforts to improve the quality and availability of African soil data, to develop field survey protocols, and to coordinate and support research and innovation on sustainable agriculture. For the non-EU countries around the Mediterranean, the PRIMA Research and Innovation Programme addresses water and agri-food systems in the Mediterranean, in order to prevent further degradation and restore damaged lands in the Southern Mediterranean. It has funded a number of projects related to soil management.

In Latin America and the Caribbean, cooperation is primarily aimed to be focused under the EUCELAC Foundation, that emphasizes sustainable agriculture and bioeconomy research in line with the EU's Horizon Europe program. Japan and Canada are also key partners. Japan seeks to align its Moonshot program with the EU's Soil Mission, while Canada contributes to designing living labs and R&I collaboration. The Soil Mission also aims to support collaboration with the FAO, particularly its Global Soil Partnership, that aims for a harmonized framework for soil data and contributes to the FAO's Global Soil Biodiversity Observatory and initiatives on soil biodiversity conservation. Finally, the Implementation Plan states that Member States' involvement in the 4per1000 initiative, launched at COP 21, established an International Research Consortium (IRC) on soil and carbon to enhance global R&I cooperation. This will be guided by the activities of the ORCaSa Horizon Europe project ("Operationalizing International Research Cooperation on Soil Carbon"), and the Global Research Alliance on Agricultural Greenhouse Gases.

Importance

The issue of soil degradation is a major concern in the Global South, affecting millions of individuals who depend on agriculture for their livelihoods. According to FAO, one-third of global agricultural land is experiencing human-caused degradation, and the rate at which this is happening is accelerating due to population growth. The areas that are most affected by soil erosion and fertility loss are those that experience the greatest decrease in yields due to climate extremes, the fastest increase in aridity, and have the highest risk for food security. Stopping soil degradation is therefore essential to achieve the goal of zero hunger. The majority of the 1.3 to 3.2 billion people affected by this issue live in poverty in developing countries. The role of the EU in this global problem cannot be neglected (European Environment Agency (EEA) et al. 2020), especially in terms of biogeochemical flows (nitrogen and phosphorus cycles), biomass flows, soil health and land system change; this is crucial to avoid an ecological poverty trap, where soil degradation could erode potential for eradicating poverty (Wackernagel et al. 2021).

DOI: 10.5281/zenodo.17430539

State of the Art

The broader state-of-the-art regarding Soil Mission Objective 7 is challenging to assess. As highlighted multiple times during the ongoing development of this outlook document, no existing study has comprehensively quantified the detailed impact of EU activities on global soil health and functions. Furthermore, there is no clear consensus on which soil functions and ecosystem services should be prioritized, or how such a footprint can be achieved.

The Soil Mission recognizes that even at the EU level, assessing the overall status of soil health remains a significant challenge. At the EU level, the combined LUCAS soil survey, soil module and soil methodology provide harmonized and statistically relevant data and protocols on the monitoring and status of key aspects of soil health (European Commission: Joint Research Centre et al. 2021). Yet, unlike other resources such as water, there is currently no legal requirement for EU member states to report on soils in a harmonized and standardized manner, although discussions on the Soil Monitoring Law are continuing. This leads to inconsistent levels of soil monitoring across the EU. Additionally, the EU soil survey faces the challenge of adapting to the evolving policy needs of both national and EU policymakers. A significant difficulty is the specific quantification of the human activity footprint in the LUCAS dataset. This is testimony to the formidable task that is ahead for achieving Soil Mission objective 7, which actually lumps all EU-based Soil Mission objectives into one single objective for soils outside the EU, along with all related harmonization and integration issues, into one worldwide perspective.

Although overarching efforts to quantify the EU impact on soils outside the EU are absent, this definitely does not imply there are no current research studies that have tried to assess the impact of EU policy and actions on soils outside of the EU. We bring together here a summary of recent efforts. We also identified key databases that offer the potential for assessing EU global soil footprint. It should be emphasized that none of the referred papers includes a comprehensive impact assessment on soil functioning and health, specifically. We emphasize that this document focuses on the footprint of food, fiber and biomass production, as these areis is the specific focus of SO7. This does not imply that no other footprints are worthwhile to investigate, as is also highlighted by multiple members of our SOLO Think Tank. As explained further in the document, expanding the Mission objective to encompass a broader definition that allows for a comprehensive assessment of impacts is worthwhile to consider in this regard. This revision would enable future policy actions to address not only biomass and food-related soil impacts but also non-biomass related influences such as pesticides, mining activities, infrastructure developments (e.g., for tourism), and climate change effects. It may also be beneficial to consider the impact of exported soil amendments (e.g., herbicides, pesticides) and waste (resulting e.g. in landfills) from the EU on soils outside the European Union.

How to establish global ecological footprint of the EU-food and biomass system

The ecological footprint (EF) of the EU-27 between 2004 and 2014, and how it exceeded regional bio-capacity, was assessed by Galli et al. (2023). The study used an extended multi-regional input–output approach (MRIO), highlighting food as a major contributor. The MRIO approach can analyse the ecological footprint (EF) and, as part of the EF, the food footprint (FF) of a region (e.g. a country, a group of countries, ...), considering both the demand and supply aspects, including trade and multiple externalities. However, it needs to be stressed that the EF was focused on resource dependence and carbon emissions, rather than soil impact. The overall conclusion was that a quarter of the EU bio-capacity for food consumption originates from non-EU countries (According to the Global Footprint Network, biocapacity stands for the regenerative capacity of our planet's ecosystems. The biocapacity metric, therefore, quantifies the

DOI: 10.5281/zenodo.17430539

renewal rate of ecosystems around the globe). Vanham et al. (2023) performed a similar approach, to track the land footprint (LF) and water footprint (WF) of food consumption in the EU. The EU LF and WF were estimated at 140-222 Mha yr^{-1} and 569-918 km^3 yr^{-1}, constituting 5-7% of global agricultural LF and 6-10% of global agricultural WF. Most of this footprint (>50%) was within the EU in all model variations. While the impact at EU level was similar in the different model variations, the non-European impact differed quite strongly according to impact region across the world, between different model runs. The study underlines the importance of a consistent and standardised methodology, since numbers differed strongly from similar earlier efforts, and were highly variable also within the study. Also here, no direct impact on soil functions was considered, but the LF clearly shows the large potential soil surface affected. It is clear that the metric used is simplified (e.g. it does not account for how land and water are managed, or when the land use was changed to agriculture) and thus contains potential inherent limitations and biases, e.g. preferring intensive land management over extensive management.

Giljum et al. (2016) identified priority areas for European resource policies using an adapted MRIO-based footprint assessment, presenting a comprehensive assessment for the EU from 1995 to 2011. The study revealed a significant shift in the origin of raw materials, with the share extracted within the EU falling from 68% in 1995 to 35% in 2011. Materials extracted in China equaled the share of EU's own material extraction by 2011. Regarding product composition, construction was confirmed as the most important sector contributing to the material footprint, followed by the group of manufacturing products based on biomass. The study highlights the fact that studies applying economy-wide material flow analysis so far mostly produced aggregated national indicators, making the results difficult to connect to policies, which are often designed for single sectors or consumption areas. No specific soil impact could be assessed from this study.

Bruckner et al. (2019) performed a global cropland footprint of the EU's non-food bio- economy. They linked the biophysical model LANDFLOW with the EXIOBASE 3 MRIO model, to provide detailed insights into product and country-specific footprint. The study revealed that two-thirds of the cropland required for the EU's non-food biomass consumption is located outside the EU, particularly in China, the US, and Indonesia, Notably, oilseeds for biofuels, detergents, and polymers represent the dominant share (39%) of the EU's non-food cropland demand. This paper provided the first assessment of the global cropland footprint of non-food products of the European Union (EU). The study concluded that if the EU Bioeconomy Strategy is to support global sustainable development, a detailed monitoring of land use displacement and spillover effects is decisive for targeted and effective EU policy making. The paper points to the fact 'that Europe stands out as the only world region that is a net-importer of the four major natural resource categories: materials, water, carbon and land'. No specific soil health effects were investigated in the paper.

MRIO?

The Multi-Regional Input-Output (MRIO) approach is an analytical technique used in economics to explore the relationships between different regions or countries within the global economy. It focuses on:

Economic interactions: MRIO models capture how industries in different regions or countries interact with each other. They account for the flow of goods and services across regional boundaries, offering a detailed view of economic dependencies and supply chain linkages.

Environmental and social Impacts: by integrating economic data with environmental and social data, MRIO models can assess the indirect effects of production and consumption activities. This includes tracing the environmental impacts, such as carbon emissions or resource usage, and social effects, like employment, associated with production processes throughout global supply chains.

Sectoral and regional Analysis: MRIO models divide the economy into sectors and regions,

DOI: 10.5281/zenodo.17430539

providing insights into the economic activities within each sector and the transactions between sectors across different regions.

https://www.footprintnetwork.org/resources/mrio/

Key papers on country-specific assessment

- Cederberg et al. (2019) focused on the environmental impacts of Swedish food consumption, specifically in relation to agrochemicals, greenhouse gas emissions and land impacts. Equally utilizing the EXIOBASE database, the research calculated novel footprint indicators for pesticides and antimicrobial veterinary medicines. Key findings revealed that a significant share of Sweden's pesticide footprint is embedded in imports, primarily from Europe and Latin America. The paper specifically points to the 'need for better data and statistics on the use of pesticides, veterinary medicines and agrochemicals residuals (especially in developing countries) as well as improved spatial data on agricultural activity to further reduce uncertainty in the environmental footprint of Swedish food consumption.'
- Kalt et al. (2021) performed an analysis tracing Austria's biomass consumption to source countries, using a physical consumption-based accounting approach, combined with national statistics and process chain modelling. 55% of Austria's total biomass consumption originated from domestic forestry or agriculture, and 30% from neighbouring countries. Products with the largest biomass footprints like beef, pork, milk, cereal products, paper, and wood fuels were primarily sourced from Central Europe. Biomass from non-EU countries accounted for about 8% of Austria's primary biomass footprint. This paper indicates the strong dependence of country- or region-specific preferences for the EU global footprint, which thus likely also accounts for the soil footprint. More specifically, the paper highlights that 'in Austria, strong preference for food and bioenergy from domestic sources is prevalent, while especially biomass imports for energy are met with scepticism.

Habitat loss and agricultural trade

Schwarzmueller and Kastner (2022) performed a study that linked agricultural trade to global loss of species. Utilizing FAOSTAT data and the Species Habitat Index (SHI) as a measure of ecosystem intactness, the research covered trade flows between 223 countries over 15 years. It showed agricultural expansion as a major driver of biodiversity loss, especially in South America, Southeast Asia, and Sub-Saharan Africa, also showing that Western Europe, North America, and the Middle East have significant biodiversity footprints outside their borders. Particular attention was paid to soybeans, palm oil, and cocoa. The authors also indicate the limitations of their study: "directly relating the species habitat loss to the production of agricultural products, we neglected the role of other drivers like logging or mining. Although agricultural expansion is by far the most widespread form of land-cover change, this introduces some uncertainty when these products are traded between different countries."

In another study linking biodiversity decline to agricultural expansion, Zabel et al. (2019) predicted global impacts of future cropland expansion and intensification on biodiversity. Although, like all others, this study was not aimed at assessing soil effects, it points to the interesting observation that 'production gains will occur at the costs of biodiversity predominantly in developing tropical regions, while Europe and North America benefit from lower world market prices without putting their own biodiversity at risk. Cropland expansion mostly affects biodiversity hotspots in Central and South America, while cropland intensification threatens biodiversity especially in Sub-Saharan Africa, India and China.' This points to the importance of prioritization to balance biomass transfers with conservation goals, preferentially first tackling the most affected regions.

DOI: 10.5281/zenodo.17430539

Analyses and Tools from the JRC

The Joint Research Centre (JRC), in collaboration with Eurostat, has developed a model to estimate the European Union's (EU) land footprint—the total area required to produce the goods consumed by its population. This model evaluates three land types: cropland, grassland, and forest land used for timber products. It accounts for both domestic land use within the EU and international land used for imported products. Over 500 food and bio-based products were individually analyzed to accurately attribute the origin of agricultural or forest land utilized in production. For instance, the cropland associated with EU imports of chocolate from Switzerland is traced back to the countries where the cocoa was originally cultivated (De Laurentiis et al. 2024, Sala et al. 2025).

Between 2014 and 2021, the EU consistently remained a net importer of cropland—land used to grow products consumed within the EU—and a net exporter of grassland, which supports products consumed outside the EU. The net trade balance for forest land varied annually, with imports and exports fluctuating within a similar range. In 2021, the EU imported approximately 50 million hectares of cropland, an area comparable to the size of Spain, while exporting about 28 million hectares. Domestically, the EU utilized 94 million hectares of cropland, measured in terms of harvested area. The primary countries supplying cropland to the EU were Argentina, Brazil, and Ukraine, with key imports including vegetable oils (such as palm and sunflower seed oil), oilseed crops (like rapeseed and soybeans), and food industry residues like oilcakes, predominantly used as animal feed.

In 2021, the average EU citizen utilized 0.26 hectares of cropland to meet their annual consumption needs for food and other bio-based products, including livestock, oils, and cotton. In contrast, the global average was approximately 0.19 hectares per person. Notably, the EU's per capita cropland use slightly exceeded the 0.25-hectare threshold per global citizen established by the Planetary Boundaries framework, a limit set to prevent irreversible environmental damage.

Overarching conclusion

The state-of-the-art analysis shows that the MRIO and the JRC approach can be good starting points for analysing and quantifying the food, feed and timber exchange between the EU and third countries, and its land footprint. A key challenge will lie in relating these mostly land cover-based assessments of footprint, to soil health and soil functioning. A good starting point here will be to rely on databases for soil properties, for which potential examples currently available are summarized below:

- www.isric.org: ISRIC is an independent foundation with a mission to serve the international community as a custodian of global soil information. It supports soil data, information and knowledge provisioning at global, national and sub- national levels for application into sustainable management of soil and land. The ISRIC library has built up a collection of around 10,000 (digitized) maps and 17,000 reports and books. ISRIC highlights standardization as a major challenge, indicating that harmonizing data from diverse sources with varying standards remains complex, affecting the consistency of global soil information. The database is also less fitting to assessing dynamic soil status: soil properties can change over time due to factors like land use and climate change, necessitating continuous updates to maintain data accuracy.
- https://www.fao.org/global-soil-partnership/regional-partnerships/en/: The Global Soil Partnership (GSP), established by the Food and Agriculture Organization (FAO), has formed Regional Soil Partnerships (RSPs) to address specific regional soil challenges and priorities. These RSPs collaborate closely with FAO Regional Offices. The RSPs link up different national soil entities (soil survey institutions, soil management institutions, soil research institutions and soil scientists working in land resources, climate change and biodiversity institutions/programmes), and could be a good starting point for local data for soil functioning assessment.

DOI: 10.5281/zenodo.17430539

- https://www.footprintnetwork.org/resources/mrio/: The Global Footprint Network leverages MRIO modelling as a tool for analysing financial flows between the major economic sectors of different countries. By integrating data from the National Footprint and Biocapacity Accounts, this approach extends to estimating resource flows, allowing for the tracking of resource movement through global supply chains. This provides valuable insights into the ecological impacts of consumption and production patterns. However, the MRIO framework operates at the country or regional level and lacks the granularity to link activities to specific soils or directly assess soil impacts.

Based on the state-of-the-art, it becomes clear why the Mission Objective 7's first sub-objective is focused on setting a clear baseline for establishing the EU's global soil footprint in line with international standards. Current state-of-the-art has not even started performing this exercise at large scale for soil functions and soil ecosystem services, rather linking trade exchanges at best to land use but not to specific ecosystem soil functions and related soil services. As emphasized by van der Putten et al. (2023), soil health laws should account for global soil connections. Establishing these connections will thus be crucial to defining future actions to improve EU soil footprint.

Knowledge Gaps

This section outlines the initial knowledge gaps (KG) as summarized from the broad state-of-the-art before the first review round in 2024. These gaps were first identified during preparatory meetings held prior to the Barcelona SOLO stakeholder meeting in Autumn 2023 and were further refined through discussions with the stakeholder group in Barcelona and beyond during stakeholder interaction moments. Thesey form the basis for the five detailed priority knowledge gaps outlined further in this document. The specific state-of-the-art is mainly detailedworked out in the priority knowledge gaps, to avoid repetition and to allow for a more actionable focus on the priority knowledge gaps.

KG1: Disentangling biomass import effects from other soil impacts

As it is currently defined, the Soil Mission does not account for land degradation resulting from industrial soil contamination, such as that caused by European factories or other polluting economic activities outside EU. Similarly, degradation from open mining activities, which are a source for imported mineral resources, is also excluded. Additionally, the impact of exporting fertilizers and pesticides from the EU, and their subsequent application to soil, may not be adequately considered.

In the Implementation Plan, it is indicated that "a first baseline has to be created by Mission activities, with specific focus on food, feed and fibre imports leading to land degradation and deforestation." A key point raised by multiple members of the Think Tank, is that the focus on biomass imports is too narrow to allow a baseline for global footprint on soils of EU actions to be formulated.

However, this does not mean that quantifying the impact of imported biomass alone would not be a valuable goal. As highlighted in the state-of-the-art, the potential land impact of the food footprint is already significant (Vanham et al. 2023).

A potential path forward has been suggested by multiple stakeholders: expanding the Mission objective to encompass a broader definition that allows for a comprehensive assessment of impacts. This revision would enable future policy actions to address not only biomass and food-related soil impacts but also non-biomass related influences such as pesticides, mining activities, infrastructure developments (e.g., for tourism), and climate change effects. It may also be beneficial to consider the impact of exported soil amendments (e.g., herbicides, pesticides) and waste (resulting e.g. in landfills) from the EU on soils outside the European Union.

DOI: 10.5281/zenodo.17430539

KG2: There is no standard soil footprinting methodology

Even at the EU level, assessing soil health across the EU remains challenging due to the lack of a legal reporting requirement, a unified definition, and standardized measurement methods. There are updated environmental footprint methods available, where land use transformation is linked to four soil properties, with a composite indicator addressing biotic production, erosion resistance, groundwater regeneration and mechanical transformation, developed by JRC. This could be a good starting point to standard soil footprint methodology development. Even if standardized soil data from non-EU countries became available (comparable to the LUCAS datasets in the EU), a significant knowledge gap remains. This gap involves identifying the specific impacts of the EU on soil health observations and further regionalizing these impacts to specific countries. Additionally, there is a need to differentiate between human and natural impacts, as well as between non-biomass and biomass-related human impacts. As clear from the state-of- the-art, the term footprint can also cause a lot of confusion, since multiple different footprint methodologies have been developed, ranging from product, consumption, land, water to environmental footprints. If a solid 'soil' footprint needs to be developed from this, it is absolutely necessary to also focus here on achieving a consistency of approaches. What is a soil footprint?

KG3: Trade-offs between soil impacts

The foot- printing objective of the Soil Mission targets multiple soil impacts lumped together, unlike the other Soil Mission objectives, which are Europe-oriented and aim for one specific soil function. As a result, a new challenge will arise, with trade-offs between regional (e.g. water cycle, land management, …) and global impacts (e.g. climate change, food security) and between different key focal impact areas, e.g. carbon sequestration and biodiversity. Even if a clear baseline for some functions is established, there will always be trade-offs with other functions (Zwetsloot et al. 2020). A sound methodology for assessing these trade-offs will have to be defined, maximizing synergies and potentially prioritizing certain soil functions in certain areas, based on clear criteria. Here, it is clear that prioritization should not select one perspective and discard the others.

KG4: Scale issues

How we moveto move from case studies to a baseline for global EU impact? How do we to link the changes in soil to EU policy and actions, and how do weto distinguish EU impact from other local and global impacts? Here is also a matter of scale: at which scale will it be possible to define the impact/EU action relation?

KG5: Impact of local and broader outside EU policy and soil governance

The EU footprint, and any actions related to reducing it, will also interact with local policy actions, particularly in regard to national definitions of "sustainability". This might complicate both the definition of potential EU remediation actions to be taken, and of footprint establishment. It will be key to carefully map and take into account local policy when defining EU actions.

KG6: Potential benefit of the use of new biotechnology, as well as agro-ecological approaches

The potential of new biotechnology and agro-ecological approaches to lower the footprint of EU food import is currently not studied in detail. This can include e.g. microbial tools (Batista and Singh 2021) and agro-ecology innovation (Hawes et al. 2021).

DOI: 10.5281/zenodo.17430539

KG7: Link to other Soil Mission objectives

Other Mission objectives focus on EU soils, mostly, without having to consider global impacts. Risk of EU solutions with a footprint abroad is strong. We need to consider the potential footprint of actions and of their interactions that will emerge from other Soil Mission objectives, in a footprint analysis. How this can beto achieve d this is currently unclear. Yet, it is clear that the outside-EU footprint objective needs to become an essential part of the soil conversations in Europe. Mechanisms need to be developed to implement the footprint analyses in EU soil policy. A sound coordination of approaches suggested within other Soil Mission objectives with their impact on global footprinting is therefore a key aim for Soil Mission objective 7.

Three Horizon Europe Cluster 6 projects have recentlyjust started, aiming to improve EU- African Union cooperation on agroforestry management for climate change adaptation and mitigation (HORIZON-CL6-2024-FARM-2FORK-01-10). Agroforestry research is related to soil mission objectives.

- Informed Decision-Making for Agroforestry Systems in Africa through a Network of Living Labs (AfroGrow)
- Strengthening rural livelihoods and resilience to climate change in Africa: innovative agroforestry integrating people, trees, crops and livestock (Galileo)
- Novel WEFE Nexus-based approaches towards agroforestry management in the Greater North African Region (Trans-Sahara)

Engagement within the Think Tank

Process for document preparation

We have organized several meetings with the different key stakeholders involved in drafting the document:

- 04/07/2023: AM, online TEAMS
  Present: Michael Obersteiner, Isabelle Verbeke, Dries Roobroeck, Ivan Janssens, Eric Struyf, Jessica Donham, Peter Laszlo
- 05/07/2023: AM, online ZOOM
  Present: Orsolya Nyárai, Detlef Gerdts, Ivan Janssens, Eric Struyf Outcome: Get to know, planning and governance of the TT.
  Discussion on key issues, challenges and opportunities that all stakeholders and TT participants identify regarding the overall objective.
- 23/11/2023: AM, online TEAMS
  Present: Michael Obersteiner, Dries Roobroeck, Eric Struyf, Vincent Dauby, Peter Laszlo, Orsolya Nyárai, Detlef Gerdts, Mirco Barbero
  Outcome: Preparation of roadmap and scoping document for Barcelona meeting, to ensure effective discussions.
- 5/12/2023, 6/12/2023 Barcelona
  Intensive discussion with stakeholders for this TT (present: Detlef Gerdts, Orsolya Nyárai, Eric Struyf, Vincent Dauby) and other TTs on the linkages of the Mission objective to other Mission goals, and identification of key challenges and knowledge gaps associated to achieving the Mission objectives.
- 28/06/2024, 3/07/2024, AM, online TEAMS
  Discussion on prioritization among the identified knowledge gaps (present: Detlef Gerdts, Orsolya Nyárai, Eric Struyf, Ivan Janssens, Gerry Lawson, Ellen Fay; Mirco Barbero, Peter Laszlo), resulting in the identification of 3 key steps necessary to enable to address this Mission objective successfully, that can serve as a base point to identify key R&I action to roll out.
- 10/10/2024, AM, online TEAMS
  Continued discussion on the prioritization, to prepare for the SOLO Sofia stakeholder meeting (present Ellen Fay, Dries Roobroeck, Peter Laszlo, Vincent Dauby, Eric Struyf, Gerry Lawson, Mirco Barbero, Zacharia Asri (intern with Ellen Fay).
- 5/11/2024, 6/11/2024 Sofia
  Intensive discussions with Eric S, Ellen Fay, Vicent Dauby and Kostadin Evegniev Atanasov and other TT and stakeholders on the prioritisation of the knowledge gaps and the visualisation of the current TT outcomes.

DOI: 10.5281/zenodo.17430539

After the Sofia meeting, there was an intense circulation of this document, with multiple new stakeholders involved. Strong input was provided by new authors Mathis Wackernagel, David Robinson and Arwyn Jones as well as all people already named above, with focus on prioritization and state-of-the-art.

Roadmap: initial knowledge gaps translated into actionable priority knowledge gaps

What is most urgently needed before the EU can start to have a better grip on its soil footprint outside the EU? Reconsidering the earlier research gaps, condensing them into the very essence of what needs to be achieved, triggered a solid consensus among the stakeholders. Compared to other soil Mission objectives, it will be clear that these R&I priority needs are surprisingly basic. The authos consider that a concerted effort to address all five key priority knowledge gaps identified, is key to enabling the first essential steps in achieving a first quantified impact of EU actions on soils worldwide.

1. We need to define current hot-spots of soil footprint for maximum impact

To identify the key impact areas of the European Union (EU) on soil functions, soil health and soil services worldwide, assessing key value chains in food and fibre industries is essential. First, a detailed global map of import of food and fibere commodities into the EU needs to be produced, by providing a total inventory of potential impacted soil surfaces per commodity, per impact region. For each of the imported commodities, imported amounts can be matched to per area productivity potential. Actions should use the most detailed available databases (a first overview of potential databases is given below). Here it is possible to build on practices developed e.g. for EUDR, which works based on a central EU Registry. Another, more advanced pathway can be based on the Land Parcel Identification system (LPIS, European Court of Auditors 2016) in each exporting country, linked to national cadastres.

Subsequently, this map needs to be linked to known effects of agricultural, forestry and agroforestry activity on soil's provision of ecosystem services, both negative and positive (this can be based e.g. on quantification systems developed in EU Horizon projects LANDMARK and BENCHMARKS). The impact will depend on the sustainability of practices applied. Footprinting should distinguish between unsustainable practices, which degrade soil, and sustainable practices, which maintain soil health. Footprints will also need to distinguish whether import of biomass requires land use change (which is typically a driver for e.g. biodiversity loss, soil erosion, soil carbon storage, soil sealing and soil carbon emissions).

In a final step, the theoretical maps produced can be matched against actual observations of soil status in the identified key impact areas. Areas where potential impact is largest, with matching observed persistent changes in soil health, can thus be identified. Remediation actions in these areas can be defined, with immediate potential for assessing the soil health status compared to baseline conditions from earlier observations. Here, it will be essential to take into consideration external factors that can affect outcomes beyond the applied practice(s), e.g. climatic stresses.

It will be essential to implement concrete solutions based on a thorough assessment of the value chains, e.g. through detailed life cycle assessments (LCAs). LCAs provide detailed insights into the environmental impacts associated with each stage of a product's life, from production to disposal. By focusing on soil-related impacts, LCAs can help identify hotspots where soil degradation is most severe. The MRIO studies, as identified earlier, have performed studies that partly reflect the approach above, albeit with following limitations: the studies currently cannot relate specific soils directly to the import and export of commodities, did not focus on soils and offer a large-scale overview of broad sectoral impact. The challenge will lie s in expanding this broad overview to include multiple soil functions, relatinge impact to specific soils through de-

DOI: 10.5281/zenodo.17430539

tailed value chain analysis, and to relate MRIO outputs to actual observed data. A brief overview of key impact studies of EU (environmental) impact worldwide is summarized below, showing again the current absence of detailed soil impacts (Table 1).

Table 1. Key impact studies of EU environmental impact worldwide.

Study	EU origin region	Outside EU impact region	Study target	Main outcome
Vanham et al. 2023	EU	World	Land footprint Water footprint No soil focus	Challenging to include latest data Strong impact of chosen 'accounting' method
Beylot et al. 2019	EU	World	Environmental footprint No soil focus	Consumption identified as key explanatory variable
Kumeh and Ramcilovic-Suominen 2023	EU	World	Deforestation No soil focus	Current regulations risk shifting responsibility to non-EU countries. Spillover risk
Galli et al. 2023	EU	World	Ecological footprint No soil focus	Food responsible for 1/3 of total ecological footprint
Giljum et al. 2016	EU	World	Focus on material extractionNo soil focus	Strong proportional increase in relative importance of non-EU materials between 1995 and 2011
Zhong et al. 2024	EU	World	Demand for agricultural landNo soil focus	Green Deal spillover effects exceed potential positive effects outside EU
Bruckner et al. 2019	EU	World	Non-food bioeconomyNo soil focus	2/3 of cropland required for EU non- food biomass is outside EU
Cederberg et al. 2019	Sweden	World and other EU	Focus on carbon footprint and pesticide footprint No soil focus	Highlights need for improved spatial data Outside EU impact mainly in Latin America
Kalt et al. 2021	Austria	World and other EU	Origin of biomass consumed No soil focus	Only 7.6 % of biomass originates outside EU
Schwarzmueller and Kastner 2022	World	World	National trade profiles for 191 consumed items No soil focus	Potential to identify key consuming countries where consumption has highest impact

Databases that can potentially be used are (non-exhaustingly) listed below:

- **Food and Agriculture Organization (FAO)** - The FAO collects and disseminates data on agriculture, forestry, fisheries, and land use. Its Global Soil Partnership (GSP) works to improve soil governance and promote sustainable soil management. The FAO's Soil Information System (SIS) and Global Soil Organic Carbon Map (GSOCmap) can be a valuable assett for mapping the EU's global soil impact.
- **International Union for Conservation of Nature (IUCN)** - The IUCN focuses on conservation and sustainable use of natural resources. Its work on ecosystem management and biodiversity, including soil health, provides potentially important data that can be used to assess the impacts of EU-related activities, for example, through the use of the Red List of Ecosystems, the Land Health Monitoring Framework, the Natural Capital Protocol, or the IUCN STAR Metric.
- **JRC Global Forest Map** - This map synthesizes information on intensive and extensive agricultural use worldwide.
- **World Resources Institute (WRI)** - The WRI provides data and analysis on global resources, including land use and soil health. Tools like the Global Forest Watch and the Aqueduct Project offer potential insight into land degradation and soil conditions.
- **Global Environment Facility (GEF)** - The GEF funds projects related to biodiversity, climate change, land degradation, and sustainable land management. The generated data could be valuable for the assessment.
- **Intergovernmental Panel on Climate Change (IPCC)** - The IPCC provides scientific assessments on climate change, including its impacts on soil health. Its reports and data can offer insights into how EU-related activities contribute to soil degradation and what mitigation measures can be adopted.
- **International Soil Reference and Information Centre (ISRIC)** - ISRIC provides global soil data and information. Its World Soil Information service offers a comprehensive database

DOI: 10.5281/zenodo.17430539

- **European Soil Data Centre (ESDAC)** - ESDAC, managed by the JRC, provides comprehensive soil data and information. It supports the development of soil policies and monitoring programs across Europe, aiding in systematic soil function assessment.
- **EUSO Dashboard** - The EUSO Soil Degradation Dashboard is an online tool developed by the JRC to monitor and assess soil degradation across Europe by providing data on factors like erosion, organic carbon loss, and land use.
- **OECD (Organisation for Economic Co-operation and Development)** - The OECD produces a wide range of research, reports, and statistics on various economic and social issues. It regularly publishes benchmarks like the OECD Economic Outlook, and the OECD Better Life Index. Data are e.g. available for nutrient (im)balance; The nutrient balance is defined as the difference between the nutrient inputs entering a farming system (mainly livestock manure and fertilisers) and the nutrient outputs leaving the system (the uptake of nutrients for crop and pasture production). A nutrient deficit (negative value) indicates declining soil fertility. A nutrient surplus (positive data) indicates a risk of polluting soil, water and air.
- **Africa Knowledge Platform** - The Africa Knowledge Platform is an initiative launched by the JRC in collaboration with various partners to consolidate and disseminate knowledge, data and resources pertinent to Africa's development. Specific focus areas include sustainable development and environmental conservation, i.e. climate change mitigation, sustainable agriculture and natural resource management.

2. We need a harmonized and regionalized soil health assessment methodology, incl. trade-offs

3. We need to disentangle food and fibre impact from other impact

Reminiscent of the EU Soil Monitoring Law (SML) that is intended to provide a comprehensive framework for monitoring soil health across the European Union, an overall framework has to be available of key soil ecosystem services to assess, and how to assess them, for outside EU soil footprinting and assessment of current impact and future potential improvements. Like the EU SML (which is currently not yet approved by EU countries), it can build on existing initiatives and ensure systematic, standardized, and obligatory soil monitoring. This standardized footprinting methodology can be linked to actions taken under priority knowledge gap 1, enabling to install a solid on-the-ground monitoring of effective soil impact related to export of key agricultural commodities to the European Union, with a primary focus on identified hotspots of European impact. This standard footprinting can be based on a solid range of already existing national and international initiatives to assess soil health and soil ecosystem services, of which a non- limiting overview is provided below. Both KGs are interlinked here, because the narrow focus of the Soil Mission on food and fibere import impact will require distinguishing these impacts from other impacts. As emphasizsed earlier, not all authors agree with this narrow focus, yet given its current central appearance in mission objective 7, it will need to be addressed.

• EU Common Agricultural Policy (EU CAP)

Under the EU CAP, farmers receiving direct payments must comply with Good Agricultural and Environmental Conditions (GAEC) standards. If they receive eco- scheme payments the expectations are greater, and higher still for some investment or agri-environment climate payments in Pillar II.

• EU CAP Network

The EU CAP Network is set up to support the implementation of the CAP Strategic Plans. The Network is a forum for National CAP Networks, organizsations, administrations, researchers, entrepreneurs and practitioners to share knowledge and information about agriculture and rural policy. The Network has three main objectives: design and implementation of the CAP Strategic Plans (CSPs), support innovation and knowledge exchange including EIP AGRI (),

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DOI: 10.5281/zenodo.17430539

and evaluation and monitoring of the CSPs. The EU CAP Network also operates thematic Focus Groups with temporary groups of selected experts focusing on a specific subject, sharing knowledge and experience, for example on 'Regenerati ve agriculture for soil health'.

• Germany

Germany has implemented the Federal Soil Protection Act (BBodSchG) and the Federal Soil Protection and Contaminated Sites Ordinance (BBodSchV), which mandate systematic soil monitoring and protection measures.

• United Kingdom

The UK has several statutory instruments that protect soil health, such as England's Agriculture Act which allows the Government to pay farmers to protect and improve soil quality and the Environmental Improvement Plan, which sets national targets for sustainably managed soils.

• France

France's national policy on soil protection is embedded in various legislative acts, including the Environmental Code. The country has developed a National Soil Monitoring Network (Réseau de Mesures de la Qualité des Sols, RMQS) that systematically assesses soil quality across different land uses.

• Hungary

The Hungarian Soil Conservation Action Plan (HSCAP) focuses on the protection of soil under agricultural cultivation. The document proposes a division of labour and responsibilities between the farmers and the state for the long-term conservation of soils and the maintenance of fertility along food chain safety principles. The HSCAP identifies the most important elements of soil protection, as follows: reasonable land use, preservation of high-quality lands, lands that are already deteriorating and that are targeted as those for improvement of related conditions; termination of soil degradation processes; maintenance and improvement of soil water balance and moisture circulation; control over substances introduced into the soil, nutrient-containing and municipal and industrial by-products.

• LUCAS (Land Use/Cover Area frame statistical Survey)

LUCAS assesses land use, land cover, and soil characteristics across the EU. The survey includes systematic soil sampling and analysis.

• Australia

Australia's National Soil Strategy aims to ensure sustainable soil management through systematic monitoring and assessment. The strategy is supported by the National Soil Monitoring Program, which provides regular and comprehensive data on soil health and functions.

• United States

The United States has several programs dedicated to soil assessment, including the Natural Resources Conservation Service (NRCS) and the Soil Health Division within the Department of Agriculture (USDA). These programs systematically monitor soil health and promote sustainable soil management practices.

• BIO-EAST

BIOEAST, the Central and Eastern European Initiative for Knowledge-based Agriculture, Aquaculture, and Forestry in the Bioeconomy is a collaborative initiative involving 11 Central and Eastern European (CEE) countries (from the Baltic through Central Europe to the Balkans) aiming to develop sustainable bioeconomy in the region. It has supported the knowledge-based interconnection of policies on biomass production and processing on a regional scale, as well as the strengthening of research and innovation capacities in Central and Eastern Europe. 11 country-specific studies have already been completed, which individually analyse the potential and development opportunities of the macro- region's biomass-based economy, in order to formulate common knowledge needs and prior-

DOI: 10.5281/zenodo.17430539

ities for a more efficient exploitation of the potential of bio-based resources in the countries of the region. The research and innovation agenda developed will greatly facilitate joint thinking and mutually supportive action between science and practice, which could lead to a more sustainable and secure use of resources in the future.

• FAO

The FAO Soils portal provides access to various soils information, including a section dedicated to making global, regional and natonal maps and databases available.

There is an essential need for the footprint soil health assessment framework to be regionalized and standardized, enabling to capture complex, site-specific trade-offs among various soil ecosystem services. It will be challenging to standardize methodologies across diverse regions while accommodating local specificities and trade- offs between competing ecosystem services (Lehmann et al. 2020). They emphasize the need for robust, scalable indicators that integrate biological, chemical, and physical properties, where this integration is often underdeveloped. Balancing the demand for rapid, cost-effective assessments with the need for depth and accuracy will be an additional potential hurdle. Translating assessments into actionable policies that consider the socio-economic and ecological trade-offs at regional level will be essential.

Robinson et al. (2024), building on five decades of experience from the UK Centre for Ecology & Hydrology (UKCEH) Countryside Surveys (CS) of Great Britain and Northern Ireland, Welsh Government, the Environment and Rural Affairs Monitoring and Modelling Programme (ERAMMP) and the England Ecosystem Survey (EES) monitoring, underscore the importance of long-term soil monitoring. Principles of robust statistical sampling, co-location of soil and vegetation sampling, and integration into policy frameworks will have to be adapted, aligned with the Driver-Pressure-State-Impact- Response (DPSIR) model. The study highlights the need to balance regional specificities with standardized metrics for assessing soil ecosystem services. This includes leveraging existing initiatives like LUCAS and integrating cost-effective, scalable soil indicators (e.g., pH, soil organic carbon) linked to ecosystem services.

4. We need to assess potential of other EU footprinting and beyond EU impact initiatives for soils

The European Union's commitment to addressing climate change and environmental degradation has spurred the development of comprehensive policies aimed at reducing carbon emissions, preserving biodiversity, and promoting sustainable practices, including outside the EU. Mechanisms such as the Carbon Border Adjustment Mechanism (CBAM), the European Union Deforestation Regulation (EUDR), and the Environmental Management and Audit Scheme (EMAS) are among the most essential. Despite their ambitious goals, challenges persist, including tracing complex supply chains and ensuring compliance with global trade rules. We here below emphasize the importance of maximally leveraging potential soil knowledge already gathered in these mechanisms to kickstart soil footprint quantification.

• CBAM

CBAM is the EU policy designed to address carbon leakage, by imposing a carbon price on imports of goods from non-EU countries. CBAM aims to ensure that the price of carbon reflects the greenhouse gas (GHG) emissions embedded in the production of goods, levelling the playing field between EU producers and their international competitors. It is currently in a transitional phase (2023-2025), and initially only applied to imports of goods whose production is carbon intensive and at most significant risk of carbon leakage: cement, iron and steel, aluminium, fertilisers, electricity and hydrogen. A similar principle for agricultural products could be implemented, that also accounts for soil management practices (e.g., deep tillage vs. no tillage). By placing a carbon price on imported agricultural products, CBAM can incentivize exporters to adopt more sustainable practices that reduce their carbon footprint. In any case, CBAM does

DOI: 10.5281/zenodo.17430539

not directly relate to or obliges to assess soil impact. Its impact on soil is more of a secondary effect through the promotion of sustainable practices and reduced emissions.

Matthews (2022) provided a first study of the potential of CBAM for targeting carbon footprint of agri-products. It came to a similar conclusion as emphasized by our first essential knowledge gap: *"there would be major practical problems in determining the appropriate level of embedded emissions in imported food products,* ***given the complexity of food supply chains where ingredients can be sourced from several countries****, all of whom may have climate policies with different levels of ambition. The potential severity of these practical problems will become clearer as experience is gained with the application of the CBAM levy to the narrower range of industrial products envisaged in the CBAM Regulation."*

Europe would also need a statutory carbon accounting scheme, building e.g. on the Agri-ETS that are currently under discussion (European Environmental Bureau 2024), before extending CBAM to agriculture and forestry can be permissible under WTO rules. Recently, the EU commission also hinted on a market-based system to encourage farmers and industry to conserve nature and restore lost biodiversity by putting a price on ecosystems. Here, it was suggested to create new financial tools to compensate farmers for the extra costs of sustainability and compensate them for taking care of soil, land, water and air. If such a system would be implemented within the EU, an equivalent should be developed for non-EU impact, to ensure that within EU practices do not negatively affect other regions (Von der Leyen 2023).

• EUDR

The EUDR aims to minimize the EU's contribution to global deforestation and forest degradation, by ensuring that products placed on the EU market are not linked to deforestation or forest degradation. EUDR covers commodities like soy, beef, palm oil, wood, cocoa, and coffee. The EUDR addresses soil functions more explicitly than CBAM. In Kumeh and Ramcilovic-Suominen (2023), EU actions on deforestation, and their efficiency, was critically evaluated. Also here, the complexity and length of supply chains were indicated as a prime challenge for tracing the origins of commodities. For example, supply chains for products like soy, palm oil, and beef often involve multiple intermediaries and can span numerous countries, complicating efforts to ensure products are deforestation- free. The EU's proposed deforestation regulation emphasizes traceability, requiring companies to provide geographic coordinates of the land used for production. However, implementing such detailed traceability measures is difficult, particularly for commodities sourced from multiple smallholders and mixed production systems.

The authors also indicate that current EU policies primarily focus on improving governance and capacity building in producing countries, which shifts the burden of deforestation onto these nations. This approach often overlooks the EU's role in driving demand for deforestation-linked products and does not adequately address the broader structural issues of overconsumption and market power imbalances. This puts attention to the fact that EU footprint outside EU could probably also be addressed through within EU actions changing consumption patterns.

• EMAS, CSDD and CSRD

Soil foot-printing can be considered as an essential part of the 'EMAS' Community eco-management and audit scheme, that aims to drive organisations towards circularity and reduce their impact on the environment, albeit not specifically related to non-EU impact. In 2021, updated Environmental Footprint (EF) methods, comprising the Product Environmental Footprint (PEF) and Organisation Environmental Footprint (OEF) and Consumption Footprints (CF) were published by the EU Commission. EF methods are based on life cycle assessment. The EF relates to soil in the land use impact category. Here, for land occupation, impact is related to changes in soil quality multiplied by area and duration. Land transformation considers the extent of changes in land properties and the area affected (changes in soil quality multiplied by the area). Recommendations specifically refer to the 'Soil quality

DOI: 10.5281/zenodo.17430539

index'. This index is the result of the aggregation, performed by JRC, of 4 indicators (biotic production, erosion resistance, mechanical filtration and groundwater replenishment) provided by the LANCA model for assessing impacts due to land use, as reported in De Laurentiis et al. (2019). The LCI (life cycle inventory) provides specific recommendations for data collection for nitrogen emissions from soil related to fertilizers, soil impact of heavy metals and pesticides, soil carbon emissions and soil carbon stocks. In this corporate framework, if avoiding soil footprint becomes institutionalized in EU, specific soil directives could become part of the Corporate Sustainability Due Diligence Directive (CSDD), that aims to ensure that companies within the EU and those supplying the EU market take responsibility for identifying, preventing, and addressing adverse environmental and human rights impacts throughout their value chains. This also relates to the Corporate Sustainability Reporting Directive (CSRD), which aims to enhance and standardize sustainability reporting by companies operating within the EU.

• EU Taxonomy regulation and the EU sustainable finance framework

The EU taxonomy regulation is a classification system that defines criteria for economic activities that are aligned with a net zero trajectory by 2050 and the broader environmental goals other than climate. By embedding soil criteria in the regulation, this could promote explicit positive soil action. Here, there is a potential link to natural capital assessment and the System of Environmental Ee conomic Accounting (SEEA), a statistical system that brings together economic and environmental information into a common framework to measure the condition of the environment. Its suitability to support regional, national and global monitoring efforts is being increasingly recognized in forums such as the UN Sustainable Development Goals, the Aichi Biodiversity Targets and the development of a Natural Capital Protocol (Obst 2015). Linking global economic models to biophysical models could also be used to assess the economic impacts of the soil degradation, as performed for soil erosion by Sartori et al. (2019).

• Nature Restoration Law

Some indicators stipulated within the EU NRL directly relate to soil health: stock of organic carbon in cropland mineral soils and share of agricultural land with high- diversity landscape features. Maximal complementarity to soil targets defined for soil footprinting should be envisaged.

• Voluntary mechanisms

Voluntary compliance mechanisms such as the Rainforest Alliance and the Roundtable on Sustainable Palm oil already consider soil impacts directly or indirectly as part of their commitment to promoting sustainable agriculture and forestry practices. Their experience should also be considered as a valuable input for EU footprinting, and maximal usage of these and other voluntary mechanisms envisaged.

• UNFCCC LULUCF carbon accounting

The emission calculation and the mitigation potential as currently used in the UNFCCC LULUCF accounting has the potential to directly link CO2 emissions to land use changes.

Based on the more detailed priority knowledge gaps defined above, following steps are key to achieve before a detailed EU footprint assessment on soils outside EU is possible:

- Develop a comprehensive mechanism for food- and fibere product supply chain impact assessment, that can link specific EU imports to specific soils affected. Based on this exercise, key commodities for more detailed soil impact study can be selected. This can be based on current efforts in CBAM and EUDR to relate EU imports to respective carbon emissions and deforestation. However, it is clear that also here, the complex supply chains are considered as a major critical challenge.
- Perform an assessment of soil impacts of the priority imported food- and fibere products on soils outside the EU. Hereto, a common method for assessing footprint has to be

DOI: 10.5281/zenodo.17430539

developed, potentially based on a wide range of existing soil footprinting standards, and on the soil quality index as proposed by JRC. Here, first specific study cases can be used to identify key soil impacts to be assessed.

- Given recent drawbacks with the implementation of e.g. the EUDR, and e.g. the complexity of extending the CBAM system to agriculture through AGRI-ETS, it will be important to aim for both realistic short-term ambition levels and more ambitious long-term ambition. This accounts for both objectives defined within the EU footprinting objective: establish the EU's global soil footprint in line with international standards, reduce the impact of EU's food, timber and biomass imports on land degradation elsewhere without creating trade-offs. A realistic pathway forward could be to focus initial footprinting only on key impact areas (e.g. priority knowledge gap 1), focus only on key soil ecosystem services and build on other initiatives (cfr. priority knowledge gaps 2 and 3). Still, long-term ambition has to remain high-level, with an accounting method that assesses within EU impact and outside EU impact in a similar way, building e.g. on the methodology that will be defined in the SML.

5. We need to define spill-over effect of EU Green Deal and other EU actions, decisions, policy

Actions within the EU that influence consumption patterns, soil stewardship, or trade relations have the potential to impact the EU's global soil footprint. These effects manifest through changes in value chains, traded biomass commodities, or the possible relocation of production to non-EU countries. An et al. (2024) have explored the often-overlooked spillover effects between 'green initiatives' implemented concurrently. By analysing 15 case studies across different countries worldwide, the authors identify both beneficial and detrimental spillover effects, revealing how one initiative can amplify or undermine another's outcomes. These findings underscore the necessity for integrated and coordinated environmental policymaking. Leveraging the spillover dynamics is crucial to enhance global conservation effectiveness, to minimize unintended harm, and to align with sustainable development goals.

To avoid negative impacts of EU actions on soils outside the EU, the Soil Mission acknowledges the need for global alignment of the soil health concept and actions to reduce and minimize the soil footprint outside the EU from imports of food, biomass, and timber. Zhong et al. (2024) further underscore that the European Green Deal (EGD) may inadvertently increase ecological harm by driving demand for an additional 23.9 million hectares of agricultural land outside the EU by 2030. This underscores the need for coordinated global policies to mitigate spillover effects. Keane et al. (2024) highlight the risks of increased compliance costs for developing nations, potentially limiting market access and impacting trade competitiveness for least developed countries (LDCs). Moreover, ensuring that deforestation-linked imports comply with stringent EU regulations introduces barriers that must be addressed through tailored capacity-building initiatives. Aligning the Soil Mission with broader international frameworks and supporting traceability systems in LDCs will be essential to minimize unintended ecological and socio-economic consequences of EU actions.

At present, the other sub-objectives of the Soil Mission primarily address specific actions and knowledge gaps necessary to improve soil health and awareness within the EU. In contrast, the footprint objective consolidates diverse issues such as soil erosion, carbon loss, soil sealing, pollution, degradation, and other soil impacts into a singular overarching goal for non-EU impacts. This broad scope complicates the footprint objective, as any proposed actions under other Soil Mission objectives (and by extension, other SOLO TT initiatives) could potentially generate spillover effects on the EU footprint.

To address this complexity, a framework must be developed to link EU soil and environmental sustainability policies with their external impacts. We argue that this framework should build on other priority knowledge gaps. A robust definition of the current footprint and a reliable methodology to assess it are essential for devising future actions to mitigate the footprint, both within non-EU countries and within the EU itself (Fig. 1).

DOI: 10.5281/zenodo.17430539

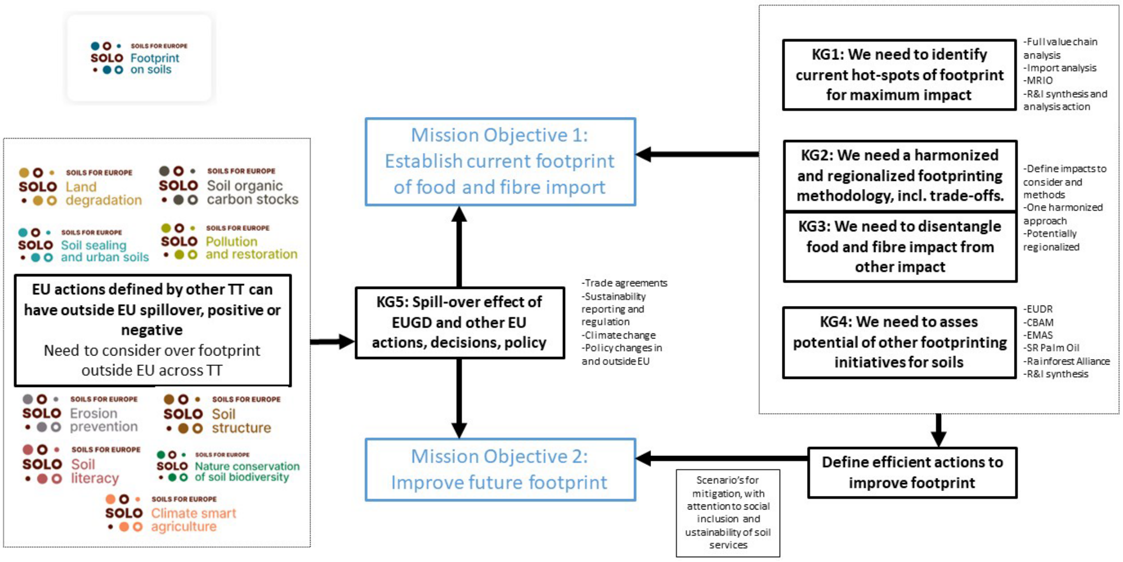

Figure 1. Overview of TT priority knowledge gaps and actions.

Prioritization

During the SOLO stakeholder meeting in Sofia (November 2024) and during an online consultation with SOLO stakeholders, it was asked to prioritize among these knowledge gaps.

This resulted in the following result, with in total 222 votes submitted by 74 stakeholders and SOLO project members.

1. Defining a harmonized footprinting methodology: 26,6% of votes;
2. Defining spill-over effects of EU actions and policy: 22.5 % of votes;
3. Defining hot-spot impact regions: 20.3 % of votes;
4. Assessing readiness of other footprinting schemes for soil footprint: 15.8 % of votes;
5. Disentangle food-fibre impacts from other impacts: 14.9 % of votes.

The prioritizsation shows that there is quite a strong consensus among stakeholders that all priority knowledge gaps are similarly important, with the strongest priority given to defining a harmonized soil footprinting methodology.

Roadmap table

Table 2 provides a roadmap overview and can be found under Suppl. material 1

Acknowledgements

We acknowledge all stakeholders who contributed to the thinking behind this document.

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DOI: 10.5281/zenodo.17430539

Soils for Europe

Outlook on the knowledge gaps related to soil literacy

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Introduction

Soil is often overlooked despite being a crucial component of the terrestrial environment. People often see it just as ‘dirt’ and as an exploitable natural resource (European Commission, Directorate-General for Environment 2021b). Moreover, the soil was, and still is, not considered as relevant as other key environmental components although is one of the three fundamentals that ensure life on land: air, water and soil. What is hidden is the significance of soils to people’s daily lives and its key role in sustaining all life on dry land of the Earth. The ‘dirt’ and ‘no value’ perception of soil may contribute to the lack of public discussion and appreciation of soils in public life, and, consequently, a political reluctance to pass laws to preserve and enhance soil health (EU Soil Observatory (EUSO) 2024). There is also little emphasis on soils in education, highlighting the need to increase public awareness and societal engagement in sustainable soil management and soil protection, which has an impact on soil literacy.

The Soil Mission Implementation plan understands soil literacy as *both a popular awareness about the importance of soil, and specialised and practice-oriented knowledge related to achieving soil health*. A more detailed definition of what soil literacy entails is provided by Johnson et al. (2020), *a combination of Attitudes, Behaviours and Competencies required to make sound decisions that promote soil health and ultimately contribute to the maintenance and enhancement of the natural environment.*

The EU Mission 'A Soil Deal for Europe' (Mission Soil) is one of five Missions funded under the EU Research and Innovation (R&I) Programme Horizon Europe. Its goal is to create 100 Living Labs and Lighthouses by 2030 to promote sustainable land and soil management in urban and rural areas. **The success of the Soil Mission depends on response and action being taken by society.** However, the current low level of soil literacy is a major barrier to achieve significant soil health improvements. Therefore, **valuing soils as part of all aspects of the environment and daily life is key**. This can be strongly supported by enabling the general public to have access to both general education on soil and targeted training for specialised needs (European Commission, Directorate-General for Environment 2021b). However, purely scientific information about soils in itself will not trigger citizen action and involvement. Rather, increased **soil literacy has to connect to people's existing values, interests, and concerns**. While some messages may be widely attractive (e.g., healthy soils underpinning achievement of physical and mental health, beautiful and healthy landscapes, good quality food), soil literacy should also be linked with specific and locally relevant concerns and should empower citizens to make a change (European Commission, Directorate-General for Environment 2021a).

Despite its importance, little prior work considers the conceptualisation and measurement of soil literacy, as well as its components, which could potentially lead to more informed and conscious decision-making by citizens towards healthier soils. Understanding the individual and community drivers that motivate people to interact with soil is crucial for informing policies aimed at facilitating initiatives that promote human-soil interaction, such as those within farming communities (Johnson et al. 2023).

Based on the importance of the development of soil literacy for the achievement of soil health, the Think Tank (a body of experts providing advice and ideas on specific issues) focuses its work in the identification of knowledge gaps in research and development around this topic. This document starts by highlighting the relevance of soil literacy for the achievement of the Soil Mission and the relation of the topic among the Think Tanks. In addition, the methodology followed by the Think Tank for the identification of members and the analysis of the knowledge gaps is described, together with the current state of the art of soil literacy.

Soil literacy in the context of the Soil Mission

The Mission's goal is underpinned by eight specific objectives, and each of those haves various policy targets. The policy targets for the "Increasing soil literacy in society across Member States" objective are:

- T. 8.1: Awareness of the societal role and value of soil is increased amongst EU citizens, including in key stakeholder groups, and policymakers.
- T. 8.2: Soil health is firmly embedded in schools and educational curricula, to enable citizens' behavioural change towards the adoption of sustainable practices both individually and collectively.
- T 8.3: Citizen involvement in soil and land-related issues is improved at all levels
- T 8.4: Practitioners and stakeholders have access to appropriate information and training to improve skills and to support the adoption of sustainable land management practices.

Soil literacy is also heavily linked to one of the four Soil Mission transversal-operational objectives: "Engage with the soil user community and society at large". The activities included in this operational objective are:

- Activity 4.1: Foster soil education across society
- Activity 4.2: Engage with and activate municipalities and regions to design their own strategies and actions for the protection of soil health
- Activity 4.3: Engage with the private sector and consumers to embed soil health in business practices
- Activity 4.4: Strengthen soil health advice and improve access to training for practi-

DOI: 10.5281/zenodo.17430539

tioners in line with Agricultural Knowledge and Innovation Systems (AKIS)

- Activity 4.5: Create citizen-led soil stewardship
- Activity 4.6: Bring soil closer to citizens' values

Considering the importance of the soil literacy topic within the Soil Mission, the Think Tank focuses its work in the definition of the soil literacy term, identification of existing frameworks and assessment of knowledge gaps related to the topic. Additionally, it is important to consider that, since soil literacy encompasses both the understanding of soil science and the engagement of the soil community and society at large, the Think Tank's activities intersect with those of the other eight Think Tanks. This interconnection between Soil Literacy and the other Think Tanks is depicted in Fig. 1.

Scoping methodology for knowledge gaps on soil literacy

The Soil Literacy Think Tank started its work with the identification of the relevant stakeholders, followed by their engagement and discussions for the identification of knowledge gaps. In May 2023, a screening process was started by ICLEI European Secretariat to identify potential stakeholders working on the topic of soil literacy at EU level. The stakeholders identified belong to the four target group areas defined in the quadruple helix model: research, governance, civil society and businesses. By October 2023, nine stakeholders had agreed to become members of the soil literacy Think Tank (a group of experts on the topic). The soil literacy Think Tank now comprises members covering a broad range of backgrounds, from soil researchers and university teachers to environmental social scientists, soil consultants, and communications experts. All the groups are represented except for business/industry. The Think Tank is designed to be dynamic and to grow and change over the lifetime of the SOLO project, therefore the screening process is ongoing and recruitment to the Think Tank will remain open.

The first official online meeting of the soil literacy Think Tank took place in October 2023, during which Think Tank members and goals were introduced. During this meeting the members agreed that soil literacy is not well defined under the Soil Mission, generating a challenge to identify gaps, bottlenecks, and activities to address it. Based on this, the members decided to meet again to have a brainstorming session around the

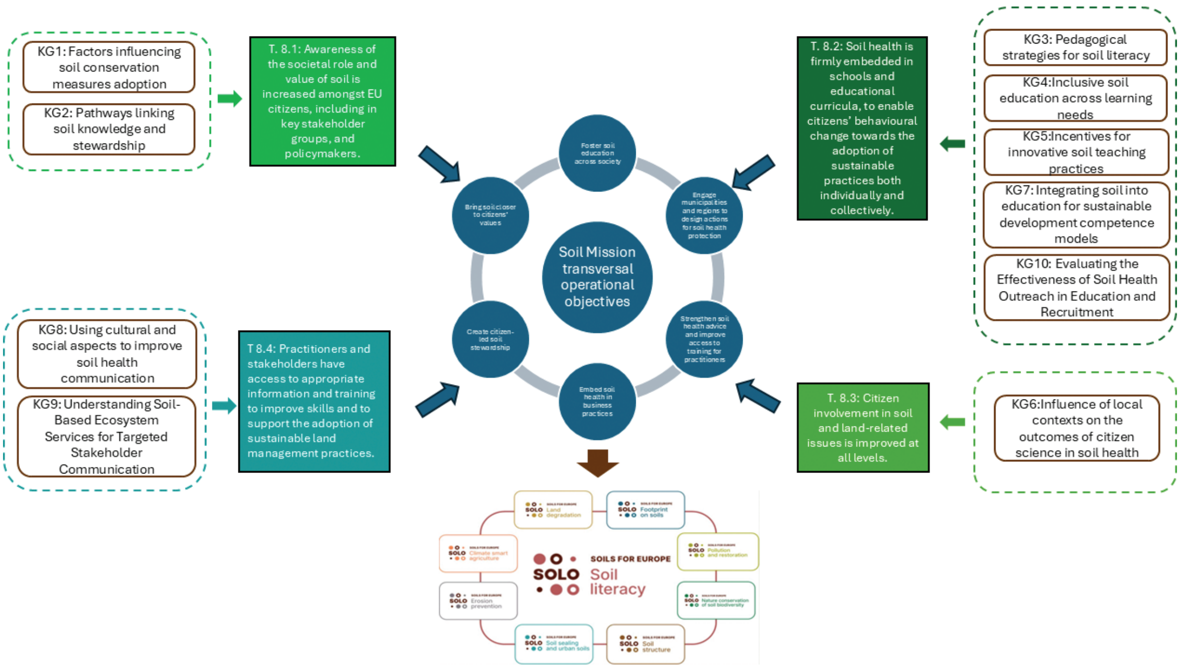

Figure 1. Soil Literacy and the Soil Mission.

DOI: 10.5281/zenodo.17430539

concept of soil literacy. This took place in November 2023 and was structured around the content of several scientific papers suggested by the Think Tank members. This information together with the main discussion points is synthesised in the present paper. Future steps might include discussions around the educational part of soil literacy, based on the collected resources and the feedback received during the review process.

Additionally, during the SOLO project conference in Barcelona in November 2023, the soil literacy Think Tank leaders had the opportunity to interact and discuss the preliminary results in a round table format with members from the other SOLO Think Tanks. The inputs collected during this session have also been included in this scoping document.

In 2024, desk research of several papers took place. The main objective of this desk research iwas the identification of research and innovation knowledge gaps related to soil literacy. As a secondary objective, this review also collected information on the actions and bottlenecks mentioned in the records related to the research and innovation knowledge gaps.

The process began on the 22nd of May of 2024 with a comprehensive search for relevant literature using **Publish or Perish** software, which facilitated the retrieval of academic papers from **Google Scholar**. The removal of duplicates was performed automatically by the software. The search was performed using a predefined search string (based on the concept of soil literacy):

- “soil” AND (“literacy” OR “capacity building” OR “training” OR “perception” OR “values” OR “awareness” OR “engagement” OR “education” OR “citizen science”)

and inclusion criteria:

- English language (the language ICLEI team members can understand)
- Open access
- Papers from 2010 ongoing
- Specifically related to the topic of soil literacy, based on the search string terms ensuring the relevance of the selected studies to the research objectives.

The screening process was divided into four stages:

1. **Identification**: A total of **898** records were identified from the Google Scholar database using Publish or Perish software.
2. **Screening**: **252** of the records, roughly the 30%, were screened based on title and abstract relevance. The remaining **646** records will be screened in 2025.
3. **Eligibility**: Following the initial screening, **64** full-text articles were assessed for eligibility against the inclusion/exclusion criteria.
4. **Included**: Finally, **23** studies were included in the analysis forming the basis for the findings in terms of research and innovation knowledge gaps, actions and bottlenecks.

This analysis was supplemented with online meetings with the Think Tank members to cross- check the relevance of the found research knowledge gaps. For Think Tank members who could not attend the online meeting in July 2024, a gGoogle survey was shared with a list of the identified knowledge gaps so they could also share their impressions. This feedback was considered to cluster or rename several of the knowledge gaps. Together with the in-person meeting in Sofia, Bulgaria, all the conversations provided highly relevant suggestions to the initial list, ending up with a total of **18 knowledge gaps,** methodology presented in **Fig. 2.**

2. State-of-the-Art

2.1 Current state of the knowledge on soil literacy

Defining the meaning of soil is a ‘complex matter’. As it is complex to define “soil health” and “soil literacy”.

Within soil science, the definition of the above terms have changed over time. Beyond the field of soil scientists, different groups have different understandings of what soils are. The way in which soils are known, represented, and understood is diverse. In different regions,

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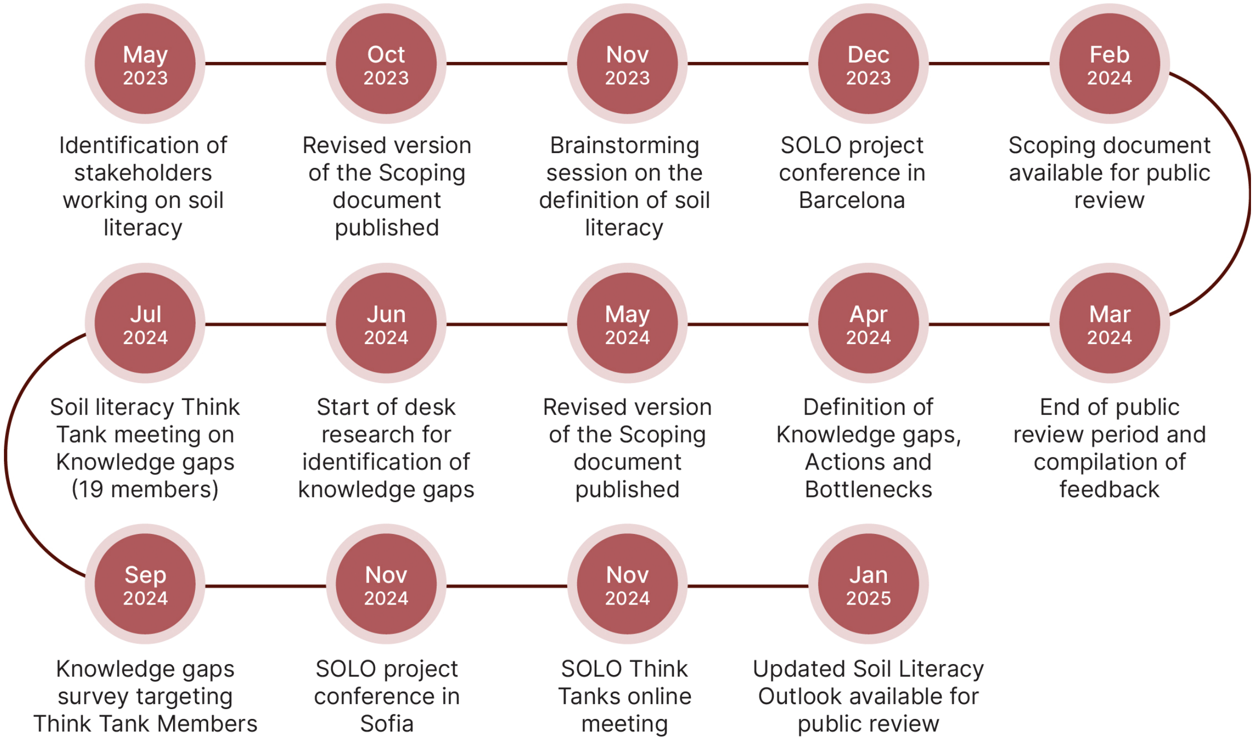

Figure 2. Soil Literacy Think Tank work-flow.

farmers, foresters, government officials, soil researchers, or environmental NGOs know soil in different ways, and attach different meanings to them (Granjou and Meulemans 2023).

There is also the historic context of how soil science has emerged and developed as a topic seeking relevance within the scientific community and governance spheres over the past one hundred years, which adds another level of complexity to the discussion. Accounts of the history of soil science usually locate the origins of the discipline in the late 1800 with Vasiliy Dokuchaev (*Rusakova et al. 2022)*, then first international soil science congresses and conferences in 1909, 1924, and 1927 (KEEN 1927). Based on Dokuchaev's work, Hans Jenny developed in the 1940's a conceptual model of soil formation factors. In the early 1900's soil related concepts started developing and being published, such as Soil fFertility, Soil Productivity and Soil Conservation. Before the 1970's soil knowledge was mainly related to agricultural practices, as technologies started developing (e.g., mechanization, chemicals, modified plant crops, namely the "first green revolution" Melillo 2012), there was a shift in this concept. This shift can also be reflected in the appearance of concepts like soil quality and soil protection in the 1970's (Mizuta et al. 2021). As a result, soil science entered a period of legitimation crisis, which extended until around 2010 in connection with the discourse on soil carbon and climate change. Soil science has re-articulated its relevance in 5 different epistemic commitments along the years (Sigl et al. 2023):

1. Communicating to policymakers, to find new ways to convey existing soil science knowledge to policymakers.
2. Internationalising soil science knowledge, to create international bodies of soil science knowledge with a broad geographical scope.
3. Rethinking soil science research by using boundary concepts, soil scientists started using concepts like ecosystem services, policy cycle, or soil health to improve communication, interaction, and collaboration

DOI: 10.5281/zenodo.17430539

beyond traditional and agrocentric soil science (creation of soil ecology).

4. The ecosystem approach in soil-related research, an approach that studies soils as part of broader ecosystems with the aim to understand interactions within and beyond soils.
5. Developing regional scenarios for (agricultural and rarely forest and urban) soil management, the goal is to use soil management as a mean to tackle societal and environmental problems without losing sight of other soil functions and ecosystem services, such as local food production or regional economic functions.

In accordance with these epistemic commitments, it can be observed that in the 1990's new concepts like soil sustainability, resilience and health were introduced. While the concept of soil security did not appear until 2013 (Mizuta et al. 2021).

The following figure summarizes the evolution of soil science, soil concepts and the epistemic commitments in a timeline Fig. 3.

As mentioned before, by "soil literacy" the EU Soil Mission recognises both a popular awareness about the importance of soil, as well as specialised and practice-oriented knowledge related to achieving soil health (European Commission, Directorate-General for Environment 2021a). By doing so, the Soil Mission seeks to establish a strong link between soil literacy and soil health. However, the main problem is that the lack of a consistent understanding of what soil is leads to complexities in defining soil health, which in turn influences the development of a concept for soil literacy.

The term "soil health" has a broader meaning and should be considered as an 'umbrella' term incorporating many different dimensions beyond ecosystem services and human health. According to the proposal for a Soil Monitoring and Resilience directive, soil health means the physical, chemical, and biological condition of the soil, determining its capacity to function as a vital living system and to provide ecosystem services (European Commission, Directorate-General for Environment 2023). This definition only relates to the functional part of the soils and obscures the different understandings and contexts that offer the great diversity of what soil health may be. The definition needs to consider how it relates to different Sustainable Development Goals (SDGs) and other environmental and socio-economic factors. In that sense, the soil literacy Think Tank agrees on the need to expand the soil health concept beyond the anthropocentric idea related to ecosystem services. It advocates for recognizing soil as a living community from which humans benefit and which they nourish. For example, 'Soil health means the physical, chemical and biological condition of the soil determining its capacity to function as a vital living system and to provide ecosystem services under different environmental and socio-economic driving forces…'. This paradigm shift would involve

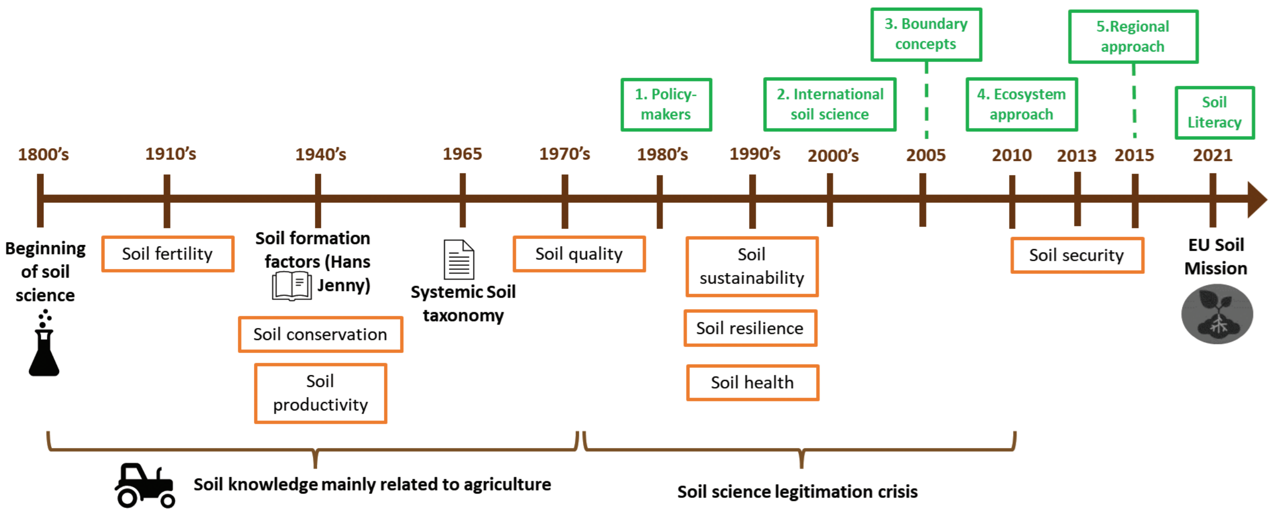

Figure 3. Soil sceince evolution timeline.

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moving from a purely anthropocentric utilitarian approach to one that is ecocentric and deontological, attributing inherent value to all soils.

As mentioned before, soil science has moved from a very local and regional perspective in which the main target of soil literacy were farmers, foresters and landowners, to a more global perspective that tries to tackle several environmental and societal challenges, and where it deals with different target audiences. Until relatively recently, there has been a linear process between researchers/policymakers/public, in which the sciences are seen as the source of knowledge about the soil which needs to be acted on by others, such as policymakers or farmers. The linear model assumes that the main group with knowledge on how soils should be managed are the scientists. However, awareness of the value or importance of soil already exists amongst other different target audiences who observe soil and land degradation taking place. For instance, community-led initiatives (CLIs) challenge this linear model by integrating traditional ecological knowledge, local practices, and experiential learning. Through grassroots networks, CLIs expand soil literacy beyond academic and agricultural contexts, offering diverse, place-based perspectives that enrich both formal education and policy development (Penha-Lopes 2019).

From all of this, we can conclude that there is not a singular soil health idea to transfer in soil literacy. But rather, due to the different viewpoints and management priorities of the target audience, there needs to be an adaptive approach to soil literacy, respectful of multiple perspectives and sources of knowledge. For instance, soil literacy for a farmer might be more practical with strong relational values, for people living in metropolitan areas, soil literacy might be linked to urban sustainability practices.

The lack of soil literacy might not only be limited to citizens, youth, students or farmers, but also extend to policymakers or planners for example. The Think Tank's preliminary desk research did not yield many results related to studies on the current status of soil literacy, or linked topics such as soil awareness raising, in Europe. This can already indicate that further research in the field is needed. Nevertheless, it is worth mentioning the work already done by soil networks like the Global, European and subregional Soil Partnerships on soil awareness and capacity building, including their collection and production of soil awareness raising and educational materials and the events they organise. Similarly, European projects such as LOESS, HuMUS, PREPSOIL, CURIOSOIL, ECHO, Links4Soils and NBSOIL work to collect the best policies and practices around soil health, and soil-related training and courses that are relevant for building the basis of knowledge around soil literacy. As relevant are the outcomes of over 18f projects under the EU LIFE programme between 2012 and 2019, see LIFE Soil Ex- Post Study - Final Report (Giandrini 2023).

Case studies outside of Europe may also serve as examples of soil literacy assessment.

For example, a soil literacy survey was conducted (Johnson et al. 2023) among a population of 3661 school children aged between 13-15 years in three African countries, Ghana, South Africa and Zimbabwe to measure their 'Attitudes, Behaviours and Competencies' to soil, which they termed 'ABC'. The survey showed that although students were generally equipped with a good attitude to (overall 52% positive) and behaviour towards soil (overall 60% engagement), they had little competency as to how to improve soil health (overall 23% knowledge). For example, less than 35% of respondents across all countries knew that soil is living. And less than 13% of students were aware of the important role of soil in climate change mitigation.

The study is supported by The ABC of Soil Literacy Report from the University of Durham (Johnson et al. 2020), which, as mentioned at the beginning of this document, provides a first definition of what "soil literacy" entails: *a combination of Attitudes (Heart), Behaviours (Hands) and Competencies (Head) required to make sound decisions that promote soil health and ultimately contribute to the maintenance and enhancement of the natural environment* (Fig. 4). Through acquired knowledge, people can develop the right attitudes, behaviours and competencies, improving soil management practices and interactions, thus increasing soil health. Additionally, the report offers approaches to mea-

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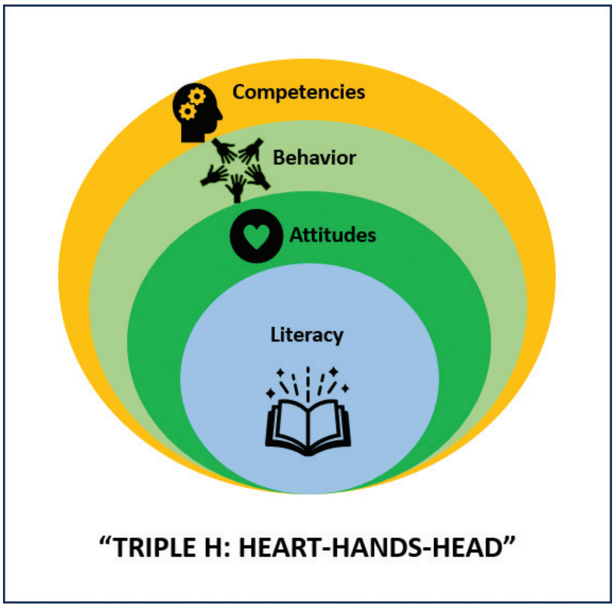

Figure 4. Components of soil literacy emphasizing the ABC (Attitudes, Behavior, Competencies; (Johnson et al. 2020)). Heart in relation to feelings-values, Hands in relation to action- management and Head in relation to abilities-capacities.

sure soil literacy levels targeting school children in three African countries. This is done through a soil literacy toolkit including a survey questionnaire, guidance on how to select samples of the target population, and advice on preparing fieldwork teams.

2.2 Recommendations for soil literacy

Soil literacy should seek to contribute to the creation of a new form of moral agency (concern for soil or soil stewardship) which would foster voluntary action (care for soil) and the implementation of mandatory and clear measures to secure soils (soil protection). A promising pathway for this is through linking responsibility for soils with already articulated governance objectives, such as reducing carbon emissions, ensuring food security, securing a functional environment, and/or land take limitation (Krzywoszynska 2023). A systemic and holistic approach to soils ensures a robust soil literacy by acknowledging the interrelation between soil and other crucial areas such as water management, circular economy, biodiversity, land use, and human and environmental health. As such, healthy soils are capable of providing a number of ecosystem services that support the achievement of the SDGs, and enhancing health. For instance, the One Health concept defined by the World Health Organisation (an integrated, unifying approach that aims to sustainably balance and optimize the health of people, animals and ecosystems) can be instrumental in establishing a connection between human health, biodiversity, and environmental health, encompassing soil.

We need to understand that most people already have knowledge of soils and about soils, although this knowledge may be different to scientific understanding. We also need to acknowledge that different forms of soil knowledge, and different levels of soil knowledge, exist unequally among the different groups and decision makers whose actions have direct or indirect impacts on soil health. Soil literacy should build upon this pre-existing knowledge and values around soils and find ways to build on actions which can lead to "healthy soils" in a just and equitable manner. In this sense, a care network model can play a key role, in which an initial attentiveness to one aspect of soils leads to a further attentiveness to other interconnected aspects. For example, farmers' attentiveness to soil structure can lead to an attentiveness to soil biota, and result in changes to land management practices so that the needs of soil biota are respected. Attentiveness can thus have a transformative effect on human-soil relations, leading, for example, to a questioning of models of land use which neglect the needs of soil organisms (Krzywoszynska 2023). In terms of engagement, when developing effective soil literacy programs, it is recommended to integrate lessons from sustainability-focused communities as well as locally/regionally relevant knowledge on soils, landscape, land use, etc. Embedding such practical, community-based learning models into soil literacy initiatives can foster a deeper, hands-on understanding of soil health.

DOI: 10.5281/zenodo.17430539

In this sense, the Fifth National Climate Assessment - the US Government's pre-eminent report on climate change impacts, risks, and responses - indicates a series of processes and actions to improve the effectiveness of engagement efforts and accessibility to climate information (Marino 2023). These can also be applied to soil literacy:

1. Co-produced or co-created research is a promising approach for soil literacy. This type of research defines non-scientific individuals as experts within their specific context, integrating community-based and scientific insights and solutions. However, integration can fail if power dynamics, goals, trust, and compensation within research teams and epistemologies are not equitable.
2. Establishing clear, measurable objectives with well-defined benchmarks or desired outcomes leads to more effective communication products and processes; bringing key stakeholders into the process at this early stage can improve effectiveness.
3. To inform real-world decision-making, information needs to be calibrated to the needs of target audiences; importantly, communicating relevant information sometimes involves translating science into understandable, accessible and actionable language, whereas in other cases it involves incorporating diverse forms of knowledge into communications products and efforts.
4. Efforts that have been successful in engaging people on climate change across existing ideological and cultural divides generally do so by addressing the things people care about most (this links to the care network model mentioned in previous paragraph).
5. Including intended target audiences throughout the process of developing communication products both promotes procedural justice and increases the likelihood that such efforts meet shared goals.
6. Engagement outcomes also strongly reflect the relationships and levels of trust between intended audiences and messengers. The use of trusted messengers increases acceptance and use of climate change risk information.
7. Pervasive uncertainty surrounding climate change continues to be a major challenge to communication (in our case soil health).

Finally, soil literacy should be addressed/considered at multiple scales and differentiate between sectors, disciplines, priorities, and age groups. One example of how this could be accomplished comes from the concept of 'Learning for Sustainability (LfS)' education or Education for Sustainability (ESD). The work is based on the green competence framework from the JRC's GreenComp document (Bianchi et al. 2022). The JRC defines 12 broad competence areas clustered on different knowledge, skills and attitude levels. Merging both competence frameworks with the European Green Deal (e.g., Farm to fork strategies), different competence areas were developed, starting from a primitive level of knowledge, skills, and attitudes to more advanced concepts. The Horizon Europe projects GreenSCENT and EC4Clim have contributed to the further refinement, expansion, and enhancement of the Green Competence Framework (GreenComp). GreenSCENT broadened the framework by aligning all competencies with the pillars of the EU Green Deal, ensuring a comprehensive approach to sustainability. Meanwhile, EC4Clim employed a multidisciplinary, transdisciplinary, and participatory process to develop and validate a European Competence Framework (ECF) for transformative change. These efforts have strengthened the applicability and relevance of GreenComp, supporting its role in fostering sustainability competencies across sectors like soil.

If some competence areas can be delineated, a target audience could then be segmented by age, interest, educational background, roles and values e.g., kindergarten, schools, youth (university, experts) or public officers. The focus would be on creating competence-based and not just content-based curricula and training programmes following a progressive multi-level approach which can be

DOI: 10.5281/zenodo.17430539

presented in a way to highlight the multidisciplinary nature of the issue and the multidimensional nature of solutions.

In summary, achieving soil health depends on the context and needs of the actors involved. There is not “one state” of soil health knowledge that we can achieve, but there is a common basic knowledge that can be shared. Additionally, the definition of soil care is necessary to achieve a societal shift in attitudes, behaviour and competencies, which should include all actors coming from different backgrounds. Fostering soil care can begin with sparking curiosity and raising awareness among all actors, encouraging them to seek knowledge and enhance soil literacy. This, in turn, supports landowners and managers in implementing and justifying sustainable practices that improve soil health (Fig. 5).

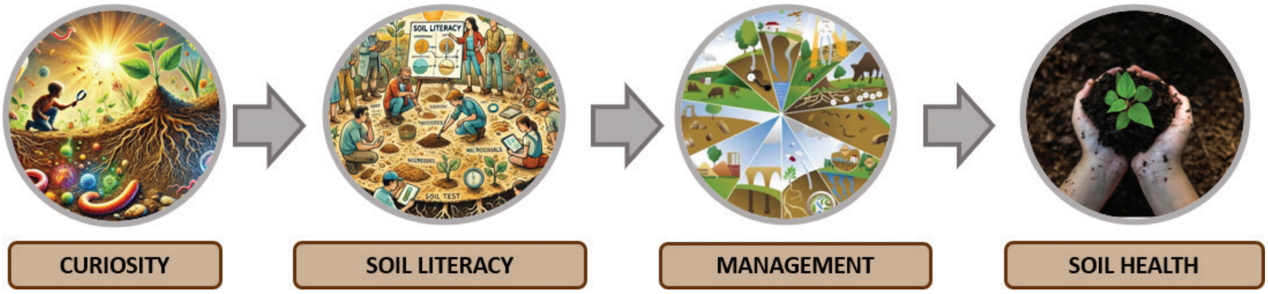

Figure 5. Awareness-to-action continuum for soil health.

3.1 Prioritization of knowledge gaps

Table 1. Ranking of the top 10 knowledge gaps identified (a full list of all identified knowledge gaps is given in section 3.3).

Rank	Knowledge gap	Type of knowledge gap
1	Further research is required to develop and validate frameworks that integrate soil as core component into Education for Sustainable Development (ESD) competence models.	Knowledge Application Gap
2	More research is needed in understanding the ecosystem services delivered by different soil types for key actor groups to improve targeted communication.	Knowledge Development Gap
3	More research is needed in evaluating the effectiveness of outreach efforts aimed at engaging primary and secondary school students, as well as the general public, in soil health topics and their impact on attracting new students to university-level soil health programs.	Knowledge Development Gap
4	More research is needed to promote understanding of the key factors that enable and/ or prevent foresters, farmers, urban planners, civil engineers and other actors to consider soil health and to adopt soil conservation practices.	Knowledge Development Gap
5	More research is needed on the development of effective pedagogical strategies to foster a deeper understanding of soil’s importance. These strategies should promote critical thinking and be state-of-the-art, hands-on and experiential.	Knowledge Development Gap
6	More research is needed in fostering the connection between soil science knowledge and soil stewardship. Instead of focusing on why the gap exists (soil stewardship paradox), studies should explore how, where, and when soil knowledge contributes to responsible soil care.	Knowledge Development Gap
7	More research is needed in assessing how local conditions affect the long-term success of citizen science initiatives in soil health, in terms of scientific data collection and public education goals and other outcomes.	Knowledge Development Gap
8	More research is needed in improving soil health communication strategies that prioritise cultural and social aspects of soils significant to diverse actors.	Knowledge Application Gap
9	More research is needed to identify the key factors that stimulate instructors to adopt new and inspiring teaching methods with regard to soil education.	Knowledge Development Gap
10	More research is needed in creating educational materials tailored to different educational levels and neurodivergent people to encourage student interest, curiosity and engagement.	Knowledge Application Gap

DOI: 10.5281/zenodo.17430539

4. Roadmap for Soil Literacy Think Tank

4.1 Key knowledge gaps

1. Further research is required to develop and validate frameworks that integrate soil as core component into Education for Sustainable Development (ESD) competence models.

Living soil can be used as an entry point to the five principles of sustainability education. The first principle, related to the valuing of biocultural diversity, draws a parallel between the vast biodiversity within soil and cultural and social diversity among human communities. By respecting and protecting soil, we can better appreciate the balance necessary to sustain biocultural diversity, fostering a deeper connection to the interdependence of life. The second one is related to the sensitiszing of all the senses. This emphasiszes the importance of engaging all the senses in the learning process. It uses soil as a metaphor of the value of ancestral knowledge and the understanding of soil through direct interaction and experimentation. The third principle, "Recognising place", highlights the need for contextualized learning in sustainability education. Soil provides an ideal lens to explore place-based factors, including geographical, historical, ecological, and cultural dimensions. These considerations help ground sustainability education in the unique characteristics of each environment, promoting a localized understanding of global challenges. The fourth one is "cultivating interconnectedness", in which soil reveals the intricate relationships between microorganisms, plants, animals, and abiotic elements, demonstrating the interconnectivity that underpins ecological balance. By studying soil, learners can develop a holistic perspective on the interconnected systems that sustain life on Earth. Finally, the fifth principle is the embracing of practical experience. The use of hands-on approaches in education can foster positive environmental behaviors and help the creation of meaningful bonds and values in relation to soil and other related environmental factors (Williams and Brown 2011).

Additionally, soil plays a key role in sustainable development and education. Soil health is an integral factor to address a wide range of topics, including public health, poverty, displacement, inequality, biodiversity loss, water retention capacity, carbon sequestration and climate change. To tackle these interconnected challenges, sustainability education must adopt an interdisciplinary and innovative approach that emphasizes soil's essential role in ecosystem services. As a fundamental resource, soil is also key to achieving the Sustainable Development Goals (SDGs) (Reyes-Sánchez 2024).

Despite the importance of soils, knowledge on different soil processes remains disconnected across various disciplines. This lack of integration hampers the development of comprehensive strategies for sustainable soil management. Research must prioritize the multifunctionality of soil health, examining its connections to major global challenges such as agricultural production, land use management, biodiversity conservation and climate change. Addressing soil degradation requires understanding the human and natural factors driving soil degradation in terms of erosion, salinization, deforestation, industrial pollution, and unsustainable farming practices.

Advancing soil literacy requires interdisciplinary and innovative educational practices that emphasisze the critical role of soil in sustainability. It is essential to train scientists and educators to effectively communicate the importance of soil across all levels of education, fostering a broader understanding of its value. Moreover it is necessary to recognize the complexity of soil science and the need to integrate it with other disciplines to create more comprehensive and cohesive educational frameworks. This will foster a more holistic understanding of soil's role in sustainability (Johnson et al. 2020).

Related Questions:

- How can soil as a core component be effectively integrated into interdisciplinary

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educational frameworks to teach sustainability concepts across diverse educational settings?

2. More research is needed in understanding the ecosystem services delivered by soils for key actor groups to improve targeted communication.

Soils are essential for maintaining ecosystem functions critical to human well-being, such as nutrient cycling, water filtration and carbon sequestration. However, despite their importance, there is a significant lack of knowledge among key social actors regarding the services provided by soils. Brevik et al. (2022) highlight that understanding the link between soil health and human life is critical to promoting sustainable soil management practices. They suggest that effective soil education programmes tailored to specific groups can help bridge this gap by demonstrating the tangible benefits of healthy soils. Increasing public and policy-maker awareness of the vital role that soils play is fundamental to the implementation of effective soil management strategies.

Psychological barriers often prevent individuals from adopting pro-environmental behaviours. According to Kollmuss and Agyeman (2002), factors such as lack of environmental awareness, social norms and a sense of alienation from nature contribute to this gap between knowledge and action. These barriers can be particularly challenging when communicating the importance of soil health, as people may not recognise the direct impact of soil degradation on their daily lives. Krasny and Tidball (2012) highlight the potential of community-based education and participatory approaches, such as urban gardening and soil restoration projects, to overcome these barriers. These initiatives not only educate participants, but also foster a deeper connection to the environment, which is essential for promoting long-term sustainable behaviours. Additionally, Hallett et al. (2017) emphasise the importance of using innovative tools such as social media, storytelling and interactive apps to engage diverse audiences and effectively communicate the value of soils.

With the increasing focus on the United Nations Sustainable Development Goals (UNSDGs), soils are becoming a key topic. Understanding the functions of soil is important for addressing global challenges and promoting sustainability Keesstra et al. (2016). However, research is still needed to further explore the knowledge gaps related to soil services supplied to different societal groups. As indicated by Brevik et al. (2022), there is an opportunity to reevaluate and redesign soil curricula by focusing on soil functions instead of the conventional emphasis on soil properties. This approach would prioritise the practical roles soil plays in ecosystems and human systems, fostering a deeper understanding of its applications and value. However, this needs to be acompanied by an analysis of the current level of soil literacy in different sectors, such as agriculture and urban planning, for developing targeted education programmes and communication campaings.

Related Questions:

- How do soils contribute to ecosystem services relevant to key actor groups, and how can these benefits be effectively communicated to enhance awareness and decision-making?

3. More research is needed in evaluating the effectiveness of outreach efforts aimed at engaging primary and secondary school students, as well as the general public, in soil health topics and their impact on attracting new students to university-level soil health programs.

The need for research to evaluate the effectiveness of outreach efforts aimed at engaging primary and secondary school students, as well as the general public, in soil health topics

DOI: 10.5281/zenodo.17430539

is becoming increasingly urgent. Soil health is fundamental to agricultural productivity, ecosystem services, and climate change resilience, yet it remains poorly understood by the general public and is often underrepresented in formal education systems. This disconnect is especially concerning as soil degradation continues to accelerate in many parts of the globe, with significant social and environmental consequences. Outreach programs offer a potential remedy, but their impact on raising awareness, changing attitudes, and influencing academic and career aspirations in soil science has not been comprehensively assessed.

In broader science education, outreach initiatives have demonstrated measurable success in enhancing engagement and academic interest among students. For instance, programs like "Shadow a Scientist" and "Present Your PhD Thesis to a 12-Year-Old" have been shown to boost students' enthusiasm for science, enhance their understanding of complex concepts, and foster interest in pursuing related academic pathways. Such initiatives also provide a two-fold benefit by improving the communication skills of participating scientists (Clark et al. 2016).

However, despite these proven models in other fields, soil science has not fully leveraged or evaluated similar outreach strategies. Research into the specific outcomes of these programs could offer valuable insights into best practices for enhancing soil literacy and engagement.

The importance of addressing this gap is highlighted by the declining enrolment in soil- related university programs globally. Sources such as Havlin et al. (2010) and Collins (2008) discuss the systemic challenges facing soil science education, including outdated curricula, insufficient public engagement, and the low visibility of soil-related careers in primary and secondary education. For example, Havlin et al. emphasize the importance of curricular revisions and targeted outreach in reversing enrolment declines, citing successful initiatives at institutions like California Polytechnic State University, where program updates led to a notable increase in student enrolment. Collins highlights the broader, national, and international scale of this issue, highlighting how declining undergraduate numbers weaken graduate programs and reduce the influx of professionals into soil science careers.

In conclusion, targeted research addressing this knowledge gap is essential for advancing soil literacy. Such studies would provide evidence-based guidance for designing outreach programs that effectively engage young learners and the general public while inspiring interest in soil-related careers.

Related Questions:

- What is the long-term impact of soil health outreach programs on primary and secondary school students' interest in pursuing soil science or related university- level education?

4.2 Prioritized knowledge gaps

- More research is needed to find suitable means to promote understanding of the key factors that enable and/or prevent foresters, farmers, urban planners, civil engineers and other actors to consider soil health and to adopt soil conservation practices.

A better understanding of the factors that lead soil actors to adopt soil, land and water conservation practices is critical for the development of successful interventions to promote sustainable soil management practices. Mango et al. (2017) provide a comprehensive analysis of such factors in the Chinyanja Triangle region of Africa. The study shows that factors such as the age and education level of the household head, agricultural extension and membership of farmer groups are critical to awareness and adoption of conservation practices. These findings suggest that social inclusion and knowledge transfer play a central role in motivating soil actors to adopt soil conservation practices. In Europe, Fantappiè et al. (2020) emphasise that economic and operational benefits - such as productivity increases and cost reductions - are key drivers for the adoption of soil conservation practices. In Sicily, farmers who perceived management benefits were more likely to perceive positive environ-

DOI: 10.5281/zenodo.17430539

mental benefits, suggesting a close link between economic efficiency and environmental awareness. Lavergne et al. (2024) draw attention to another important issue: the under-representation of studies on the global South, particularly on environmental issues. This knowledge gap could affect the development of global solutions to soil degradation if certain regions are not sufficiently included. Furthermore, Charzyński et al. (2022) highlight the need for educational programmes to focus more on concrete solutions to soil degradation problems in order to create a deeper awareness and commitment to sustainable practices among farmers. This suggests that both cultural and practice-based approaches are needed to promote the adoption of sustainable soil conservation measures.

Nonetheless, soil degradation is a multifaceted problem, influenced by activities in many sectors, including urban development, forestry, infrastructure construction and industrial activities. For example, urban expansion is a growing threat. Research by Barbero-Sierra et al. (2013) highlights that "urban sprawl in peri-urban areas leads to the fragmentation of fertile soils, reducing their productivity and ecological functions". This is of particular concern, as urban settlements often expand into areas of high soil fertility, making "urban sprawl the most active agent of desertification in Spain". Soil sealing - covering soil with impermeable materials for roads, buildings and other infrastructure - is one of the most devastating threats to soil ecosystem services, effectively halting critical functions such as water filtration, carbon sequestration and nutrient cycling.

Unsustainable forestry practices, such as clear-cutting, contribute to soil erosion, loss of organic matter and disruption of soil structure, increasing the risk of landslides and reducing biodiversity. According to Pimentel and Kounang (1998), "deforestation and poor land management practices accelerate soil erosion rates, often beyond the natural regeneration capacity of the soil".

The effects of industrial pollution are also critical. Research by Nagajyoti et al. (2010) shows that "heavy metal contamination from industrial activities leads to deterioration of soil microbial activity, nutrient cycling and plant productivity, resulting in long-term soil degradation".

Given these multiple threats, it is essential to adopt a holistic approach to soil protection that addresses the drivers of soil degradation across all sectors. This includes not only promoting sustainable agricultural practices, but also promoting sustainable urban planning, responsible forest management and the development of green infrastructure to mitigate soil sealing, erosion and pollution. By broadening the focus of key factors that enable and/or prevent soil protection efforts, we can more effectively safeguard soil health as a critical resource for environmental resilience, climate regulation and human well-being.

Related Questions:

1. What socio-economic and cultural factors influence and prevent the adoption of soil conservation practices by farmers and other stakeholder groups?
2. How can education be adapted to promote and enable the adoption of sustainable practices?

- More research is needed on the development of effective pedagogical strategies to foster a deeper understanding of soil's importance, promoting critical thinking and be state-of-the-art, hands-on and experiential.

In addition to the lack of integration of soil science and management practices within the educational curricula, traditional teaching approaches are often relying on passive learning methods that primarily involve receiving information without active participation and are only able to provide basic knowledge. These approaches fail to develop critical thinking and problem solving skills in students, which are required to understand and address the complexity of soil related issues and processes (Amador 2019). The complexity of soil science derives from the need to understand the interaction of the different components like atmosphere, biosphere, hydrosphere, lithosphere, ecosphere and anthroposphere, requiring students and practitioners to have the knowledge to under-

DOI: 10.5281/zenodo.17430539

stand these interactions, while also possessing the skills to collaborate across the various disciplines (Al-Ismaily et al. 2023). Therefore, the study of soil science requires contextualised, holistic, practical and experiential learning approaches centred around living soil as a way to foster a deeper ecological understanding and improvement of sustainability literacy (Williams and Brown 2011).

Practical and hands-on experience in soil science teaching can be understood in two ways: The first one refers to more practical approaches in the learning process of students, focusing on innovative pedagogical techniques like Problem Based Learning (PBL), Soil Skills (SSK) or Soil Judging Contest (SJC). The second approach focuses on more experience based and hands-on methods, in which students get the opportunity to directly observe and interact with soil.

As well, inquiry-based learning approaches, such as Soil Skills (SSK) and Soil Judging Contest (SJC) can enhance the engagement of students, creating dynamic learning environments. SJCs are a program based on competition, teams will evaluate soil properties and features (e.g. soil texture, structure, color) and make informed judgements based on their knowledge and observations. While, in the case of SSK, students have to address real case studies by applying interdisciplinary approaches, considering the relations between soil, water, landscape and community to solve problems (Al-Ismaily et al. 2023).

Moreover, the use of hands-on and interactive activities with soil has an advantage, as experiences associated with unstructured activity in a natural setting can positively influence environmental behaviour and can produce meaningful relationships with nature and the environment, especially for children (Williams and Brown 2011).

This can also be implemented through project based learning approaches like fieldwork or field trips, including soil sampling and measuring of parameters, which generates higher levels of student engagement and a better understanding of soils as an ecosystem component and how it can be related to other disciplines (Aran 2024). The use of practical and interactive experience approaches can further foster awareness and understanding of the value of soil, increasing soil stewardship (Williams and Brown 2011). Studies indicated that early interaction with natural environments plays a crucial role in shaping social engagement, well-being, and lifelong connections with nature. Children who regularly experience nature tend to be more active, engage more with their communities, and develop higher self-esteem and resilience to stress. These benefits extend into adulthood, fostering continued participation in social and environmental initiatives (Hartig et al. 2014).

Related Questions:

1. What pedagogical strategies can be integrated to improve the understanding of soils in different age group students?
2. How can pedagogical strategies be adapted depending on students/ schools location (students from urban or rural areas, living near mountains or plains, agricultural practices around them..?
3. What isi the place of soil in the holistic approach of environmental (and socio-economic) undertanding?

- More research is needed in fostering the connection between soil science knowledge and soil stewardship. Instead of focusing on why the gap exists (soil stewardship paradox), studies should explore how, where, and when soil knowledge contributes to responsible soil care.

There is a growing need for research that bridges the gap between soil science knowledge and soil stewardship. The idea of “stewardship” involves the conscientious and responsible management of resources entrusted to one’s care. In this sense, a mix of factors such as socio-economic conditions, policy frameworks, cultural perceptions, and education systems play significant roles in determining whether knowledge is translated into action (Prager and Posthumus 2011).

The study by Neaman et al. (2024) points out that agricultural professionals, particularly those with academic or urban backgrounds, may possess extensive technical soil knowledge without a corresponding level of care for soil

DOI: 10.5281/zenodo.17430539

health. This disconnect calls for further research to clarify the relationship between knowledge acquisition and stewardship behaviours. As well, studies on environmental knowledge and behaviour, such as those by Kollmuss and Agyeman (2002), illustrate this "knowledge-action gap" across environmental fields. They suggest that psychological, social, and contextual factors heavily influence whether knowledge translates to stewardship behaviours. However, while much focus has been placed on the reasons behind the soil stewardship paradox— a disparity between knowledge without a corresponding sense of care and care without a corresponding level of knowledge (Neaman et al. 2024) —less attention has been given to understanding how, where, and when soil knowledge can be effectively applied to promote sustainable soil management practices.

Identifying the specific contexts and conditions in which different forms of soil knowledge (e.g., scientific, traditional, or experiential) leads to responsible soil care would contribute significantly to fostering a culture of stewardship and ensuring that soil management practices are both effective and sustainable. Furthermore, understanding the pathways that link soil knowledge to action could uncover mechanisms for improving the adoption of sustainable soil practices.

Related Questions:

1. How can different forms of soil knowledge (scientific, historical traditional, experiential) contribute to responsible soil care?

2. What are the specific contexts and conditions in which soil knowledge leads to effective stewardship practices?

- More research is needed in assessing how local conditions affect the long- term success of citizen science initiatives in soil health, in terms of scientific data collection and public education goals and other outcomes.

In terms of soil health, there is a lack of targets and indicators for its monitoring in the global context as well as a lack of a common method, or a unified protocol that can be applied. Additionally, soil monitoring presents another degree of complexity as soil quality presents a high variability in cities across short distances, making regulation difficult (Price et al. 2024). An extra challenge is the lack of recognition from both policy makers and the general public of the importance of healthy soils as an environmental asset of equal importance as clean air and water. Participatory approaches can play a key role to engage the general public in scientific inquiries about soils and soil health, which can cultivate awareness and soil values (Price et al. 2024).

It is important to keep in mind that integrating citizen science into soil health initiatives presents both opportunities and challenges, particularly in ensuring the scientific validity of data collection and the effectiveness of proposed remediation methods. While citizen engagement can enhance data collection and public awareness, there is a risk that misinterpretations of scientific facts and the promotion of unproven soil management practices may undermine long-term outcomes. For example, certain remediation techniques, despite being scientifically discredited, continue to gain traction among non- experts. Addressing this challenge requires structured collaboration between soil experts and citizen initiatives, fostering mutual understanding through capacity-building efforts, transparent communication, and scientifically sound methodologies. Further research is needed to assess how local conditions influence the success of such collaborations and to develop strategies that align citizen-driven efforts with evidence-based soil health management.

Participatory approaches can be classified into three categories based on the phase of involvement of participants or the general public: contributory, collaborative or co- created. Contributory approaches are designed by scientists, and participants are used to contribute to data. In cCollaborative approaches, participants can also help refine the project design or analyse the data. In co-created approaches, participants are involved from the initial design and conceptualization of the research question (Wadoux and Mcbratney 2023).

A study highlighted by the European Joint Programme SOIL emphasizes the underutilized

DOI: 10.5281/zenodo.17430539

role of participatory citizen science in advancing soil health. The research showcases how engaging the public not only enhances data collection but also fosters a broader commitment to sustainable soil management (Mason et al. 2024). In addition, Hou et al. (2020) highlight the potential of emerging technologies, including 5G telecommunications, big data, and machine learning, to revolutionize soil data collection and analysis.

In general, further research is needed to assess how local conditions influence the success of such collaborations and to develop strategies that align citizen-driven efforts with evidence-based soil health management and how they can effectively contribute to data collection and public education goals.

Related Questions:

1. How do local environmental, social, and policy conditions influence the long-term success of citizen science initiatives in soil health, particularly in ensuring scientifically valid data collection and effective public education?
2. What strategies can enhance the integration of robust citizen science into soil health monitoring while ensuring scientific rigor, preventing misinformation, and fostering productive collaboration between soil experts and the public?

- More research is needed in improving soil health communication strategies that prioritise cultural and social aspects of soils significant to diverse actors.

Understanding effective strategies for soil science communication and outreach is essential for fostering meaningful engagement with diverse social actors. Brevik et al. (2022) highlight the importance of integrating cultural and social dimensions in soil education to enhance public connectivity to soil, suggesting that storytelling and social media engagement can resonate with non-experts by linking soil to quality of life and cultural heritage. This finding highlights the need to align communication strategies with the cultural and social contexts of different audiences, using concepts like soil health and terroir, which make soil science more accessible and meaningful.

Research indicates that individuals who are dissatisfied with their financial situation are more likely to express skepticism toward eco-social policies and prioritize welfare-related concerns over environmental challenges. This suggests that lower-income groups may perceive climate and environmental action as a less immediate necessity compared to economic security. Conversely, as financial stability improves, individuals are more inclined toward environmental advocacy, as they can afford to prioritize post-materialistic values. However, financial satisfaction alone does not necessarily lead to stronger eco- social engagement (Otto and Gugushvili 2020).

Additionally, trust in public institutions and egalitarian values appear to be more decisive in shaping environmental attitudes than factors such as income, education, or place of residence. This highlights the importance of addressing ideological and perceptual divides when fostering broad-based environmental engagement and communication strategies (Otto and Gugushvili 2020).

Furthermore, socioeconomic disadvantage—characterized by lower education and income levels—as well as spatial marginalization, such as living in rural or economically declining areas, should be better recognized in the design and implementation of climate and environmental policies in the EU. Ensuring equitable access to knowledge and opportunities is crucial to fostering inclusive participation across all societal groups (Schüle et al. 2019).

Effective communication on soil health requires strategies that resonate with diverse audiences and foster meaningful connections to the environment. Evidence from the GEN Ecovillage Impact Assessment highlights the importance of participatory, narrative and experiential communication methods (Kovasna and Mattos 2017). Ecovillages, traditional or intentional communities that aim to become more environmentally sustainable, show that soil health messages are most effective when embedded in personal stories, cultural practices and community experiences. The study notes that “76% of ecovillages regularly engage in educational activities related

DOI: 10.5281/zenodo.17430539

to environmental sustainability, using both formal and informal channels". One key strategy is to use storytelling as a tool for environmental communication. By sharing stories about local food systems, land regeneration and community resilience, complex ecological concepts become more accessible. These approaches can be researched and adapted to soil literacy campaigns to foster emotional connections and lasting awareness.

However, current approaches are often limited in addressing how empirical and scientific knowledge can be communicated and integrated in ways that foster genuine engagement. As Krzywoszynska (2019) explains, soil science communication frequently overlooks the knowledge and meaning-making practices within local communities. Her work on sustainable soil management in England reveals that a focus on scientific knowledge alone can isolate local, experiential understandings of soil and calls for strategies that consider these community-rooted insights.

Furthermore, Krasny and Tidball (2012) explore how civic ecology practices provide a model for community-centred stewardship, illustrating the importance of grounding environmental communication within local, culturally relevant practices. In this context, soil communication must not only inform but also foster connections that enable diverse stakeholders to see their roles in soil stewardship. These insights point to a significant knowledge gap in soil science outreach: few studies have explored how communication strategies might effectively initiate step-by-step dialogues that bridge scientific and local knowledge frameworks.

Addressing this gap may aid in developing inclusive, context-sensitive communication strategies that better support sustainable soil management practices across diverse regions and communities.

Related Questions:

1. What strategies can create dialogue between empirical, practical, and scientific knowledge about soils to engage diverse social actors?
2. How can local knowledge be integrated into soil science communication to foster connections between different social actors and produce stewardship?

- More research is needed to identify the key factors that stimulate instructors to adopt new and inspiring teaching methods with regard to soil education.

Soil science education faces the challenge of developing innovative teaching methods that both convey specialised knowledge and engage a broader audience from various disciplines. While Brevik et al. (2022) highlight the need to organise content in ways that combine in-depth knowledge with interdisciplinary perspectives, studies investigating how educators can be motivated to implement these methods remain sparse. The integration of practice-oriented approaches, such as experiential learning emphasised by Williams and Brown (2011), offers an opportunity to make complex soil topics tangible and to underscore their significance for issues such as climate adaptation, biodiversity, and human health.

Particularly, the idea of presenting soil not solely as a scientific subject but as a nexus between ecological and social systems underscores the relevance of interdisciplinary approaches. Brevik et al. (2022) stress that making soil knowledge accessible to students from other disciplines is crucial for raising awareness of soil's importance in global sustainability challenges. However, educators often face practical challenges such as time and resource constraints, which make it difficult to integrate innovative methods into their teaching practices. Krzic et al. (2024) demonstrate how incorporating the concept of "Soil Health" into curricula in Canada can strengthen the connection between soil science and sustainability education, yet also reveal the practical barriers that hinder educators from broadly implementing these concepts.

Furthermore, there is insufficient clarity on which resources and incentives would most effectively support educators. While practical, hands-on approaches such as field studies and the use of soil biocrusts de Lima and Rojas (2022) demonstrate significant potential,

DOI: 10.5281/zenodo.17430539

questions remain about how to embed these methods into interdisciplinary frameworks. Field (2017) proposes deepening soil understanding through concepts such as "knowing soil, knowing about soil, being aware of soil" across different levels of education. This could not only achieve specialised learning objectives but also enhance the broader relevance and acceptance of soil topics. Combining practice-oriented and interdisciplinary approaches thus represents a promising avenue for advancing soil science education. However, there is a lack of systematic studies exploring how these approaches can be effectively implemented, the factors influencing educators' acceptance of such methods, and ways to overcome practical barriers.

Related Questions:

1. What factors influence the willingness of educators to adopt practice- oriented and interdisciplinary teaching methods in soil science education?
2. What educational resources or incentives are most effective in promoting the adoption of innovative teaching methods?
3. How can practical barriers, such as time and resource constraints, be overcome to support the implementation of these approaches?

- More research is needed in creating educational materials tailored to different educational levels and neurodivergent people to encourage student interest, curiosity and engagement.

Developing educational materials tailored to diverse educational levels and to individual needs (e.g. neurodivergent individuals) is essential for fostering student engagement. Neurodivergent students, including those with autism spectrum disorder (ASD) and attention-deficit/hyperactivity disorder (ADHD), often encounter systemic barriers in traditional educational settings, which can impede their learning experiences and engagement (Durgungoz and Durgungoz 2025).

Despite this, existing studies often lack comprehensive strategies for adapting curricula to accommodate diverse learning preferences and sensory sensitivities, which are crucial for effective engagement. Additionally, there is still a lack of understanding regarding how such efforts not only impact immediate learning processes but also influence academic success, well-being, successful transitions, and life outcomes beyond higher education (McDowall and Kiseleva 2024).

This research gap is especially relevant for all students at different education levels, from young learners in primary education, to adults with advanced knowledge. In early education, structured and concrete learning materials help build a strong foundation. As students move through secondary and higher education, learning becomes more abstract and complex to encourage critical thinking and independence.

When it comes to soil education, there is a lack of standardized and adaptable materials across these levels. While resources exist, such as the British Society of Soil Science's educational materials or the Soils 4 Teachers platform, they are not widely integrated into curricula and vary in content and accessibility. This inconsistency creates gaps in soil literacy, making it difficult to ensure that students at all levels gain a comprehensive understanding of soil's role in environmental and societal systems. Developing structured, adaptable, and standardized soil education materials tailored to different learner needs and levels is essential for improving engagement and learning outcomes.

Related Questions:

1. What strategies can be used to develop standardized and inclusive soil education materials that accommodate diverse learning needs and levels, including those of neurodivergent students?

4.3 Overview table

The Soil Literacy Think Tank has identified a total of 18 Knowledge gaps, which are presented in the following table along with the respective Actions and Bottlenecks. Additionally, these Knowledge Gaps have been classified in Fig. 7 following the Attitudes (Heart), Behaviours (Hands) and

DOI: 10.5281/zenodo.17430539

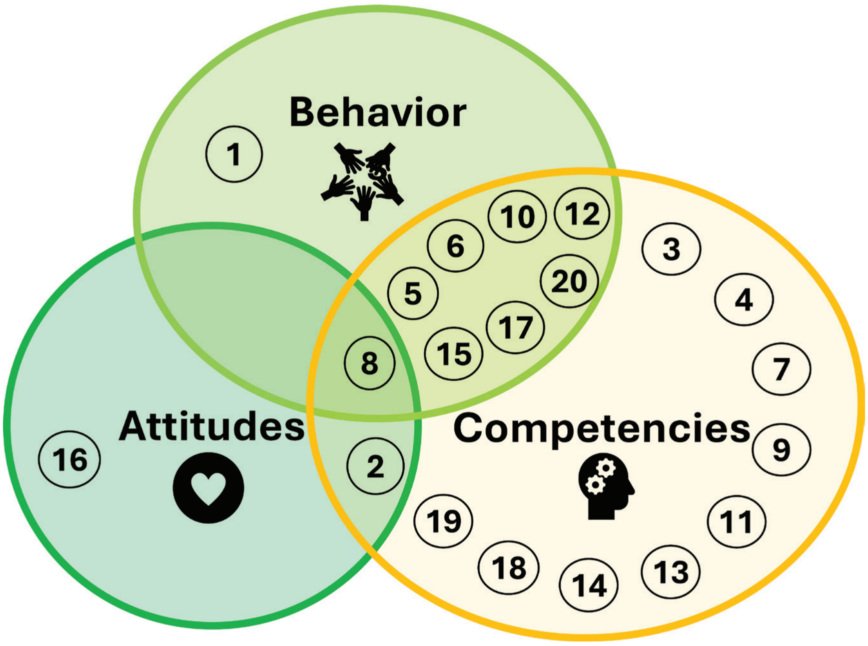

Figure 6. Classification of the Soil Literacy Knowledge gaps within the Attitudes, Behaviour, Competencies framework (ABC).

Competencies (Head) framework referenced in previous sections from the ABC of Soil Literacy Report from the University of Durham (Johnson et al. 2020). These classifications allow a better understanding of the societal impact of the identified Knowledge Gaps. As it is presented in Fig. 6, the majority of the knowledge gaps are targeting Behaviours and Competencies, with a few that have relevance across the three ABC components. For future work, the Think Tank will take into consideration the identification of more Knowledge Gaps targeting the Attitudes component of the framework.

Soil literacy knowledge gaps overview table

An overview of the soil literacy knowledge gaps and can be found under Suppl. material 1.

Acknowledgements

We would also like to express our gratitude to other individuals who contributed to the completion of this second version of the soil literacy Think Tank scoping document, which will be continuously updated every year throughout the lifespan of the project.

Contributions by: Froukje Rienks, Head of PR & Science communication at the Neth- erlands Institute of Ecology (NIOO-KNAW); Abdul Otman, Council member Global Ecovillage Network, ECOLISE; Tanja Mimmo, from the Free University of Bozen-Bolzano (ECHO Project); Teresa Nóvoa, from MED – Mediterranean Institute for Agriculture, Environment and Develop-ment & CHANGE – Global Change and Sustainability Institute, Institute for Advanced Studies and Research, Universidade de Évora Samantha Grover, from Department of Applied Chemistry and Environmental Science, RMIT University; Monica A. Farfan, from German Centre for Integra-tive Biodiversity Research (iDiv); and Tóth Gergely from Institute of Advanced Studies, Kőszeg and the Institute for Soil Sciences, HUN-REN ATK, Budapest.

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DOI: 10.5281/zenodo.17430539

DOI: 10.5281/zenodo.17430539

Outlook on the knowledge gaps to improve nature conservation of soil biodiversity

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1. Introduction

There has been an increasing awareness of the importance of soil biodiversity and the ecosystem services it provides (Mikola et al. 2002, Eisenhauer et al. 2024). Approximately 59% of all biodiversity on the planet comprises belowground-dwelling organisms (Anthony et al.

2023), ranging from microorganisms to vertebrate species (FAO et al. 2021, Anthony et al. 2023). The activities of soil biodiversity (soil biota) support the delivery of various ecosystem services, such as, for example, carbon sequestration, nutrient cycling, prevention of soil erosion, pest control, and cleaning of air and water (Pulleman et al. 2012, Creamer et al. 2022, Banerjee and van der Heijden 2023). However, soil biodiversity is currently threatened by changing climate extremes, intensive agriculture and forestry, as well as pollution and soil sealing in urban environments (Tsiafouli et al. 2015, FAO et al. 2021, Beaumelle et al. 2023, Phillips et al. 2024). Protecting soil biodiversity, and thus its ecosystem functions and services, through conservation will have positive effects in achieving the Sustainability Development Goals (SDGs) (Bach et al. 2020), including increasing water quality and food security, among others (FAO et al. 2021, Köninger et al. 2022).

Soil life is key to the survival and health of life and ecosystems on Earth (Banerjee and van der Heijden 2023, Singh et al. 2023) but it is under-protected (Guerra et al. 2022), leaving its associated ecosystem functions and services under-protected as well. Soil biodiversity is defined by FAO et al. (2021) "as the variety of life belowground, from genes and species to the communities they form, as well as the ecological complexes to which they contribute and to which they belong, from soil micro-habitats to landscapes".

There is little research on the efficacy of current conservation methods and frameworks specifically for soil biodiversity protection (Guerra et al. 2022). Recent work did not find positive effects of current conservation practices on nematode diversity (Ciobanu et al. 2019) and soil biodiversity and its ecosystem functions (Zeiss et al. 2022). While biodiversity-friendly management approaches, such as ecological intensification (Kleijn et al. 2019), regenerative agriculture and agroecology (Barrios et al. 2023, FAO 2023, Grilli et al. 2023) are receiving increasing attention, studies focused on conservation of soil biodiversity and its ecosystem functions are still limited (Bardgett and Van Der Putten 2014, FAO et al. 2021, Zeiss et al. 2022). Thus, there is a stark need for identifying knowledge gaps and new research and innovation to help protect and conserve soil biodiversity, the ecosystem services they provide, and their impact on human health and economics.

This Think Tank (TT) aims to further the Soil Mission's research and innovation agenda through the TT's collective knowledge of the ecological importance of soil biodiversity to soil health and its economic and societal impacts, which also contributes to the EU Soil Strategy and the EU biodiversity strategy. The integrative nature of soil biodiversity conservation across the Mission objectives is a key feature because soil biodiversity is the basis of soil functions, processes, and ecosystem services. Led by researchers from Lund University with support from University of Leipzig, TT members represent the areas of research and policy from universities, NGOs, and policy bodies. Through literature reviews and transdisciplinary work with stakeholders and researchers, this TT is assessing knowledge gaps and developing possibilities for research and innovation for future roadmaps to improve knowledge on the nature conservation of soil biodiversity. The TT has identified current knowledge and knowledge gaps with the following steps:

- A literature review of the most recent research into gaps of knowledge regarding Nature Conservation of Soil Biodiversity (September 2023)
- Online workshop with TT stakeholders (November 2023)
- Joint TT meeting, Barcelona, Spain (December 2023)
- Reassessment of knowledge gaps after public review (January 2024)
- Joint TT meeting, Sofia, Bulgaria (November 2024)
- Literature analysis on soil ecology and conservation biology (Summer 2024)
- Online meeting with Nature Conservation TT stakeholders (January 2025)

DOI: 10.5281/zenodo.17430539

2. State-of-the-Art on Nature Conservation of Soil Biodiversity

2.1 Current State of Knowledge on nature conservation of soil biodiversity

"*Soil, at any scale, is complex: opaque, composed of a myriad of organo-minerals, roots, large and small organisms, and exhibiting truly impressive gradients in its biology, chemistry and physics over large and small spatial ranges.*" – Young and Bengough 2018

Soil biodiversity, ecosystem functions, and ecosystem services

The scientific scope of ecosystems ecology today emphasises functions and the role that soil biodiversity plays in understanding decomposition, energy fluxes, or resilience aspects (e.g. Eisenhauer et al. 2022). However, linking the diversity of soil organisms to ecosystem functions at different spatial and temporal scales in real ecosystems is a difficult process due to the sheer number of individuals and interactions, therefore studies produce mixed results in the types and magnitude of effects (de Vries et al. 2013, Nielsen et al. 2011, Schuldt et al. 2018, Veen et al. 2019, Delgado-Baquerizo et al. 2020, FAO et al. 2021).

The importance of soil biodiversity for ecosystem functioning has been investigated in experimental systems, with support found for the importance of the soil food web to ecosystem functions (de Vries et al. 2013, Wagg et al. 2014). Soil ecosystem research developed from soil food web ecology, where it is understood that both direct and indirect interactions among soil organisms determine how the diversity of species and functional groups influence the energy and nutrients fluxes in soil (de Ruiter et al. 1993, de Ruiter et al. 1998, Jochum and Eisenhauer 2021). The research in the 1970s and -80s, such as the Man and the Biosphere (MAB) programme of UNESCO, created knowledge on the significance of soil organisms in ecosystem functioning globally (Persson and Lohm 1977). Of note are the Tropical Soil Biology and Fertility Programme (TSBF), established in 1984 under the patronage of the MAB programme of UNESCO, and the Decade of the Tropics initiative of the International Union of Biological Sciences (IUBS). The objective of this last programme was to develop appropriate and innovative approaches for sustaining tropical soil fertility through the management of biological processes and organic resources (Woomer and Swift 1994).

Economic values of soil ecosystem services associated with soil biodiversity lack optimised and standardised models. There are general frameworks of valuation of soil biodiversity (Pascual et al. 2015, Plaas et al. 2019, Bartkowski et al. 2020, Han et al. 2023, Johnson et al. 2024), but this has not become an important focus in awareness raising nor in policy or land management decision making as of yet (Phillips et al. 2020). Thorough assessments of the contributions of soil organisms to ecosystem services are urgently needed to guide decisions regarding tradeoffs in choosing areas to conserve and conservation methods. Fig. 1 details the overall linkage of soil biodiversity to ecosystem functions, services to humans, and the feedback of land management and conservation practices by human society on soil biodiversity. Changes to agriculture, land management, environmental regulations, and stewardship can be made to protect soil biodiversity, its ecosystem functions, and services to humans and support the Sustainability Development Goals of the UN (Bach et al. 2020; Fig. 2)

Conservation

Because we have incomplete, yet useful, information on the taxonomic and functional diversity in soils, this leads to challenges in understanding how to effectively protect and preserve functions through conservation and restoration practices.

DOI: 10.5281/zenodo.17430539

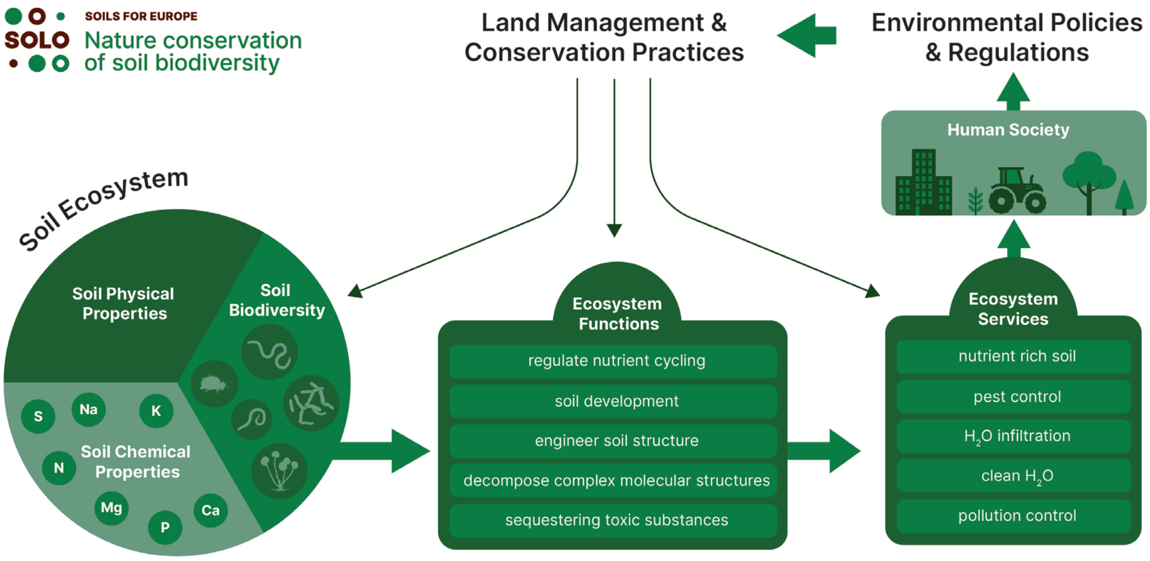

Figure 1. Soil biodiversity is integral to ecosystem functions and benefits human society through its associated ecosystem services. In turn, conservation and land-management policy and decision making directly impact soils biodiversity and, indirectly, ecosystem functions and services. Credit: Pensoft Publishers.

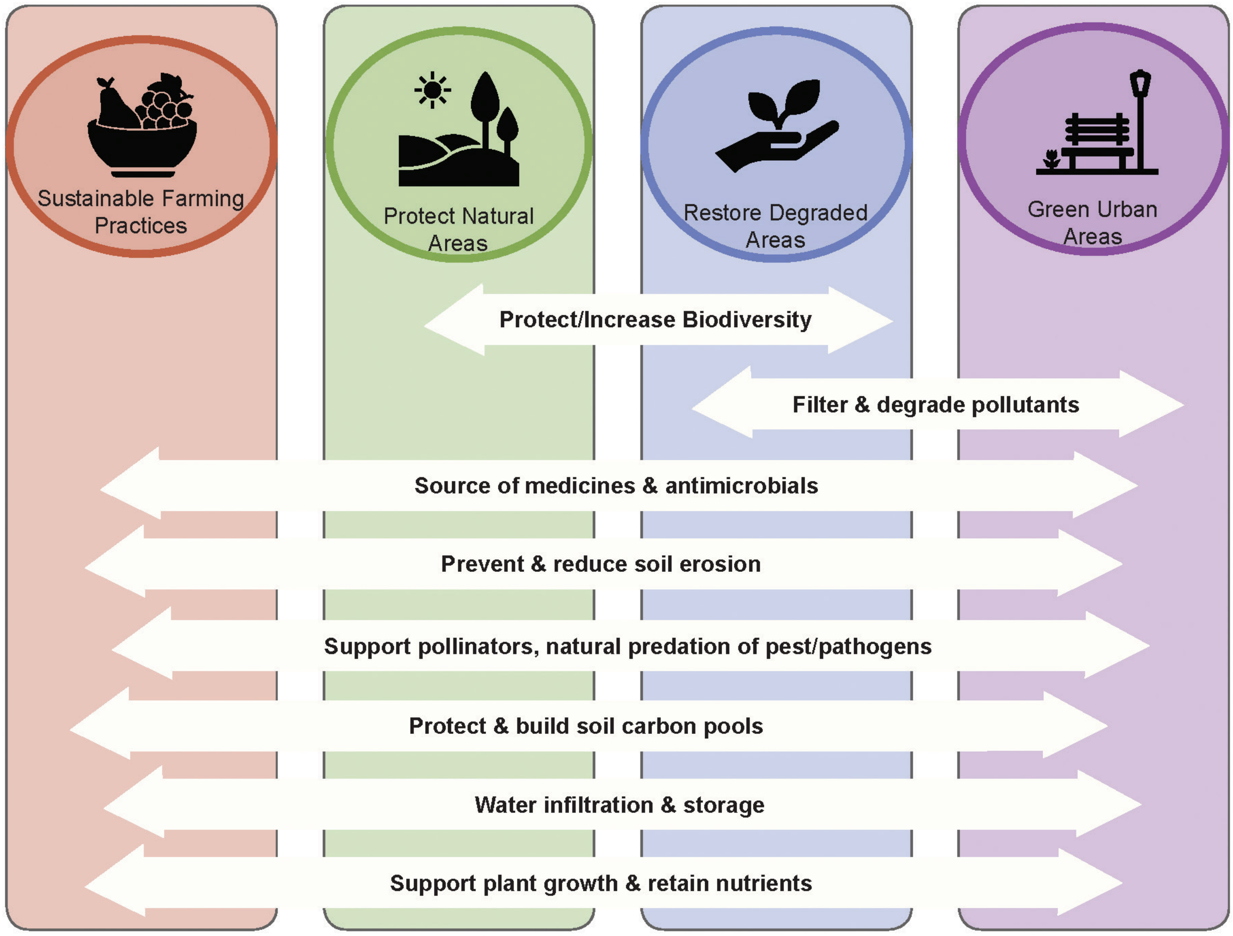

Figure 2. Areas where action can be taken that support soil biodiversity and its associated ecosystem services. From Bach et al. 2020. Image credit: K.S. Ramirez, E.M. Bach.

DOI: 10.5281/zenodo.17430539

Table 1. The IUCN categories of protected areas (Lausche 2011).

Category No.	Description
Category Ia	Strict nature reserves function to preserve the biodiversity and sometimes geomorphological features of an area and allow only light human traffic
Category Ib	Wilderness areas are generally larger than nature reserves and have less stringent regulations
Category II	National Parks - areas protected for the preservation of ecosystem functions but with more allowance for human visitation
Category III	Protection of national monuments or features, either natural or influenced by humans
Category IV	Area managed for continuous protection of a species or habitat
Category V	Protected landscape or seascape with the allowance of for-profit activities
Category VI	Areas protected but with the sustainable use of natural resources

The Convention on Biological Diversity (CBD) definition of protected area is: "A geographically defined area, which is designated or regulated and managed to achieve specific conservation objectives". These areas are chosen for conservation for varying desired outcomes, both ecological and cultural. The IUCN categorises protected areas depending on the level of protection they provide (Table 1, Lausche 2011).

This system of categorising continues to be utilised even though it focuses on management practices rather than monitoring biodiversity outcomes (Boitani et al. 2008), particularly soil biodiversity conservation (Guerra et al. 2022, Zeiss et al. 2022). Most conservation areas were designated to protect specific plants and animals, with soil ecosystems not being directly considered while developing such protected environments. Cameron et al. (2018) found a considerable mismatch between aboveground and belowground biodiversity at the global scale. This means, if only areas with the highest aboveground diversity are protected, a large portion of soil biodiversity-rich areas may be at risk for degradation. Zeiss et al. (2022) examined soil biodiversity and ecosystem services across nature conservation areas and non-conserved areas across Europe and found that, while conserved areas are assumed to have positive effects on non-target ecosystems, there was no evidence of these conservation measures having positive influence on soil ecosystem functions. In evaluating the aims in selecting these sites, multiple reasons were found for the lack of observed effects. Firstly, there is a lack of emphasis on site selection for conservation based on the value of soil biodiversity and associated ecosystem services as evidenced by language used in selection justifications. Secondly, Zeiss et al. (2022) found an emphasis on threats to chemical and physical properties of soil in the protected area selection language instead of an emphasis on the value of the belowground ecosystems and the functions that influence abiotic factors.

Integration of conservation into sustainable use

Protected areas have long been the most important tools in biodiversity conservation. However, with increased focus on ecosystem services and human well-being, the focus is changing from protection of (threatened) species towards sustainable use (Hummel et al. 2019), and thus ecosystem functions and services. Sustainable use is defined as "the use of components of biological diversity in a way and at a rate that does not lead to the long-term decline of biological diversity, thereby maintaining its potential to meet the needs and aspirations of present and future generations" (European Commission 1993). This approach is widely used, especially in agriculture and forestry. Examples of integration of conservation are e.g. agroecological intensification, agroforestry, and extensive forest technical management.

The EU Common Agricultural Policy (CAP) provides several suggestions on how to protect soil biodiversity through soil health, e.g. enhanced crop rotations, reduced tillage, cover crops and fertiliser regulations. However, discussions and data concerning soils and their

DOI: 10.5281/zenodo.17430539

sustainable use have long focused on either their vulnerability to physical impacts (e.g., soil erosion, mining) or improvements to their food production potential (e.g., through fertilisation). Narrow perspectives, often missing indicators and disconnectedness from environmental monitoring, limit a wider discussion on the ecological importance of soil biodiversity and its role in maintaining ecosystem functioning beyond food production systems (Guerra et al. 2021b). This prevailing emphasis has also prevented soils from becoming a more mainstream nature conservation priority (Guerra et al. 2021b).

Soil biodiversity conservation, policy, and indicators

The conservation status of most soil organisms is almost completely unknown, with most soil taxa yet to be described. Among 17 EU directives, a review determined that most of the legislations and strategies only address the threat to soil biodiversity indirectly, e.g. the Biodiversity Strategy for 2030 and the Farm to Fork strategy (Köninger et al. 2022). These address issues, e.g. soil pollution, that could benefit soil biodiversity, but they do not explicitly address soil biodiversity per se. Soil monitoring schemes in the EU member states often only focus on chemical and physical properties, but rarely on soil biology (Köninger et al. 2022). Out of the 196 parties to the CBD, only a few had national targets in years 2011–2022 that consider conservation of soil and soil biodiversity (Guerra et al. 2021b). Therefore, monitoring and the careful choice of indicators to monitor soil biodiversity are of key importance. Though with the coming EU soil monitoring and resilience directive, further data sets of soil biodiversity across all land use will secure data on soil biodiversity (COM/2023/416 final 2023).

The Land Use and Land Cover Survey (LUCAS) action from the European Commission (2025) enables EU wide sampling of soils and land use. Eight hundred and eighty-five 885 locations were sampled in 2018 and 2021/2022 to study taxonomical and functional soil biodiversity by metabarcoding. This may allow data and development of a suite of biodiversity indicators that may be considered for official inclusion in assessments and reviews of EU policies (Köninger et al. 2023, Labouyrie et al. 2023). The identification of indicator organisms of biodiversity or deteriorated communities is still an unanswered research question that currently is receiving a lot of focus (e.g. the EU Horizon project SOB4ES: https://sob4es.eu/).

Soil biodiversity conservation awareness and information sharing

At regional and local levels, awareness raising targeted to stakeholders, general public and in education is needed for understanding of the importance of soil biodiversity and to support for regional and EU-wide policies and regulations on soil biodiversity conservation. To contribute to conservation and sustainable management of soil biodiversity, several initiatives and research networks have been established over the years. Agreements on and definitions of the conservation of soil biodiversity were brought to the international agenda by FAO in cooperation with the Convention on Biological Diversity (CBD) with the International Initiative for the Conservation and Sustainable Use of Soil Biodiversity, established in 2002. In 2012, the FAO set up the Global Soil Partnership (GSP) to further increase attention and work on soils, due to their vital importance for food and agriculture. Another important effort is the Global Soil Biodiversity Initiative (GSBI), an independent, third-party network of scientists, policymakers, and citizens. Established in 2011, the GSBI provides a platform for assessing and synthesising knowledge on soil biodiversity and was called upon by the CBD to support post-2020 soil biodiversity monitoring and target development, among others.

3. Roadmap for nature conservation of soil biodiversity

3.1 Key knowledge gaps

Key knowledge gaps, as judged through a combined Think Tank prioritization process, are shown in Table 2.

DOI: 10.5281/zenodo.17430539

Table 2. Ranking of the top 10 knowledge gaps identified (a full list of all identified knowledge gaps is given in section 3.3).

Rank	Knowledge gap	Type of knowledge gap
1	Standardisation of soil biodiversity monitoring methods	Knowledge Development Gap
2	Economic valuation of soil biodiversity	Knowledge Development Gap
3	Effective conservation and restoration methods	Knowledge Development Gap
4	Effective conservation frameworks	Knowledge Development Gap
5	Public awareness of soil biodiversity	Knowledge Application Gap
6	Effective soil biodiversity conservation strategies	Knowledge Application Gap
7	Minimum dataset to index soil biodiversity	Knowledge Development Gap
8	Threats to soil biodiversity	Knowledge Development Gap
9	Species taxonomic identity and ecology	Knowledge Development Gap
10	Spatial & temporal distribution of soil biodiversity	Knowledge Development Gap

3.1.1 Standardisation of soil biodiversity monitoring methods

One of the major barriers in the capacity to develop effective soil biodiversity conservation practices and policies is the lack of standardised methods of field data collection. Identifying a set of soil indicators to track soil conservation is critical to provide a set of standard tools and a public repository to monitor trends in the biomass, abundance and diversity of soil biota and its functions. The level of methodological standardisation largely depends on the aspect and type of soil organism to be measured. For instance, the characterization of microbial biomass is largely lacking a widely accepted and standardised method in the literature, with multiple coexisting methods. The standardisation of methods for both fully monitoring and conserving soil biodiversity have been raised as concerns multiple times, and many alternatives have been put forth (Gardi et al. 2009, de Bello et al. 2010, Cluzeau et al. 2012, Pulleman et al. 2012, Griffiths et al. 2016).

For effective, standardised monitoring, there is a need for the combination and integration of indicators to adequately interpret the state of soil biodiversity and trends in the 6functions of soil organisms. There are registered ISO standards for a number of the soil organisms and suggestions for methodological approaches to measure structural and functional diversity of soil organisms, and to identify gaps and methodological improvements so as to cross data sets generated worldwide (Römbke et al. 2018). Thus, for key aspects of soil microbes such as taxonomic and functional diversity, next generation sequencing "omics" have imposed a relative level of standardisation over the last two decades with many researchers using the same technology (e.g., Miseq and Hiseq Illumina) and similar primer sets (e.g., 16s, V3-V5 regions). Such standardiszation has been further supported by significant initiatives such as the Earth Microbiome Project (earthmicrobiome) which already suggested standardised protocols more than a decade ago. This knowledge is key to providing standardised information for supporting soil conservation worldwide.

Soil biodiversity indicators need to be easy to standardize and widely available to researchers worldwide (Guerra et al. 2021b). For instance, previous studies have proposed combinations of indicators such as the evaluation of abundance and diversity of earthworms and Collembola, along with determination of microbial respiration (Bispo et al. 2009, Pulleman et al. 2012). Nematode communities have also been used successfully to evaluate the functional and ecological conditions of soils (e.g. Ferris 2010). Cluzeau et al. (2012), found that soil fauna and microbial biomass were adequate as bioindicators for land-use types and their managements, showing that, depending on the depth of the functional aspects that are examined, the dataset need not be large to discern differences in how the land is used and managed.

DOI: 10.5281/zenodo.17430539

Table 3. Summary of research and proposals for indicators for continental-scale monitoring of soil biodiversity, assessment methodology, and proposed context for application suggested by the source authors.

Biodiversity indicators (assessment method)	Ecosystem function indicators	Context	Source
Microbial biomass; 16S rRNA; pcaH; Nematode (abundance); Nematode (richness); Acari (abundance); Collembola (abundance); Collembola (richness); Earthworm (abundance); Earthworm (richness); Total macrofauna		Association of biological indicators to land use and management	Cluzeau et al. 2012
Nematode (molecular); Earthworm (morphological); Collembola (morphological); Enchytraeids (morphological); Mites (morphological); Functional genes; Fungi: ergosterol; Microbial T-RFLP; PLFA	Nematode (molecular); Earthworm (morphological); Collembola (morphological); Enchytraeids (morphological); Mites (morphological); Functional genes; Nitrification; Potentially mineralisable N; Hot-water extractable C; Bait lamina; Extra-cellular enzyme activity; Microbial respiration; Water infiltration; DNA abundance; Resilience	Policy-relevant; ecologically-relevant	Griffiths et al. 2016
Tier 1: Earthworm species; Collembola species Tier 2: Macrofauna; Mites; Nematode functional diversity; Bacterial and fungal diversity by DNA or PLFA	Tier 1: soil respiration Tier 2: Bacterial and fungal activity	European-scale monitoring	Römbke et al. 2006, Bispo et al. 2009
Bacteria & Archaea (molecular); Fungi (molecular); Fungi (morphological); Mites (molecular); Pyrosequencing of soil DNA; Molecular microbial biomass	Functional genes (targeting antibiotic producers); Pyrosequencing of soil DNA; Chip Technology (gene regulation); Multiple enzyme assay; Multiple substrate induced respiration	European-scale monitoring	Stone et al. 2016

Table 3 summarises the indicators by biodiversity and functional categories that are examples of indicators to adequately represent the state of soil biodiversity in general and the method used to rank these indicators. The problem is that many of these indicators are not easy to measure and researchers have not yet agreed on a golden standard to measure such parameters.

Modern statistical analyses such as Species Distribution Modelling, General Dissimilarity Modelling and Niche-Space Modelling can estimate values of biodiversity, but will require (1) more trans-European observational soil-biodiversity data collation, including open-access data sharing (e.g., Michener 2015, Tedersoo et al. 2021), (2) improved thematic precision of the association between observational soil-biodiversity data and environmental and climate metadata (e.g. Bhusal et al. 2015), as well as (3) capacity building in the form of training expertise, time-consuming tasks of data collation, running the models species by species for the large range of extant soil species, and the human resources necessary to do accurate assessments.

Actions to fill knowledge gaps in standardising soil biodiversity monitoring methods

- Harmonisation and standardisation of methods and data management
    - Cooperation and discussions between soil ecologists and other disciplines
    - 7Methods standardisation should inform plans for current and future monitoring and ‘assessments’, such as the Soil Biodiversity Observation Network (Soil BON) and the Global Soil Biodiversity Observatory (GLOSOB) (Nielsen et al. 2011, Eisenhauer et al. 2021, Guerra et al. 2022)
    - The use of sequencing technology to track soil microbial diversity
    - In the case of larger organisms and soil processes, there are also critical limitations when it comes to data standardiszation and comparison across databases

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- Develop and enhance soil biodiversity indicators
- Identify examples of standard and easy to measure biodiversity indicators
- Develop a comprehensive information system of soil biodiversity

Bottlenecks to filling knowledge gaps in standardising soil biodiversity monitoring methods

The barriers to standardising methods for monitoring and conserving biodiversity are relatively few, though a transformation towards open access and agreements on standardisation is needed. There is a wide range of methodologies for measuring soil biodiversity and functions, including ISO standards, as mentioned above, but although many suggestions have been made for suites of parameters, there is still a lack of common agreement on one suite that is valid across science and end users of the assessment. However, not all methods work for all climatic conditions or soil types (van der Putten et al. 2012).

3.1.2 The valuation of soil biodiversity

The value of soil biodiversity and ecosystem services to environmental and human well- being can be a powerful tool to 1) educate and influence public understanding of the costs and the benefits of protecting diverse soil life, 2) incentivise farmers/growers to protect soil biodiversity-based ecosystem services for public as well as private reasons, and 3) provide a context for the benefits and tradeoffs associated with soil biodiversity conservation and land management decision-making and policy development as their efficacy is evaluated over time (Daily et al. 2009, Fig. 3; Brady et al. 2019).

There are several approaches to valuing soil biodiversity as a bundle of ecosystem services, but a common, comprehensive framework is needed (Jónsson and Davíðsdóttir 2016). An economic value depends on the agent of the valuation so it can be one value to the land manager and another to the value of public goods (Scherzinger et al. 2024). The Ttotal Economic Value (TEV) method values not only the flow of the services but also the insurance values, or the values associated with certain-world and uncertain-world values in the future demand or supply buffering against external environmental disturbance (Pascual et al. 2015, Bartkowski 2017, Johnson et al. 2024). The most common tools to determine use values here are market pricing, net factor method, cost- based methods, travel cost method, and hedonic pricing (Jousset et al. 2017). In agriculture the value of soil biodiversity has been used in a general way of how biodiversity enhances production and through that its value (Brady et al. 2015, Brady et al. 2019).

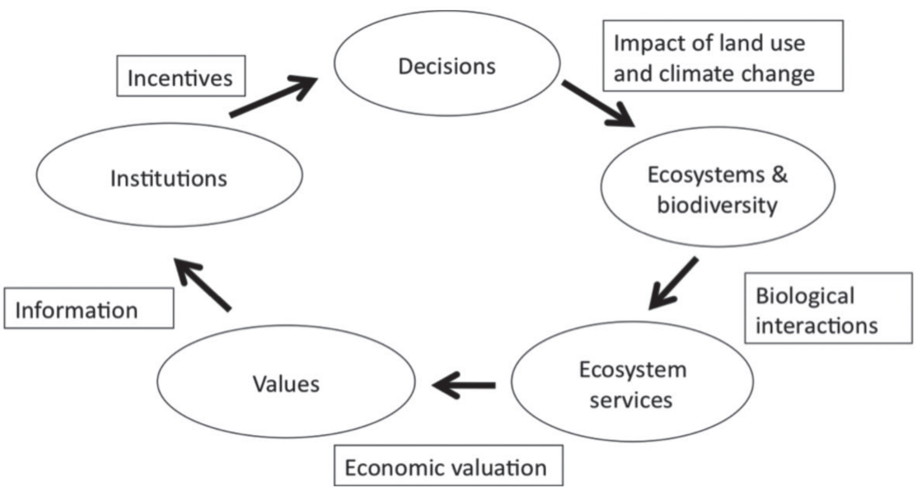

Figure 3. A decision loop which can be used for policy development accounting for soil biodiversity and the resulting ecosystem services and their values when taking actions and decision on natural capital (modified from Daily et al. 2009).

DOI: 10.5281/zenodo.17430539

To date, scattered knowledge exists on the valuation of soil-based and biodiversity-based ecosystem services, but there are *no studies on full evaluations of soil-biodiversity-based ecosystem services*. A combination of multiple methods may be fruitful, though further development of valuation methodologies is needed. The concept of different Soil- mediated Contributions to People (SmCPs) have been used to value ecosystem services and drivers of change e.g. land use (Johnson et al. 2024). Soil-biodiversity-based ecosystem services valuations could follow the example by Bartkowski et al. (2020) who define soil-based ecosystem services as "the outcomes of soil processes that economic valuation focuses on in order to make visible the benefits of soils for human well-being and inform sustainable soil management and policy." In defining it this way, Bartkowski et al. (2020) could associate soil-based ecosystem services to the Common International Classification of Ecosystem Services tool (CICES V5.1) (Haines-Young and Potschin 2018). Since this is a framework for all types of ecosystem service valuation, Bartkowski et al. (2020) used a subset of biotic ecosystem service categories for evaluation.

An alternative to this method is to use the mMultiple studies proposing methodologies to support the use of a valuation framework that goes beyond the strictly ecosystem services model to a use of multiple methods in combination or more holistic, integrated models combining monetary and non-monetary benefits (Pascual et al. 2015, Bartkowski et al. 2020, Han et al. 2023, Johnson et al. 2024). Non-monetary methods, which include preference-based and cultural valuation methods, have the advantage of being more inclusive of multiple value systems and of diverse stakeholders. Preference-based valuation methods are more accurate in acknowledging the public good value of soil biodiversity and soil health (Bartkowski et al. 2020).

Fixed monetary estimates of biodiversity have been estimated, but this is without an agent for the valuation and instead compared to values for e.g. food production (Pimentel et al. 1997, Jónsson and Davíðsdóttir 2016, van der Putten et al. 2012). They suggest that maintaining a diversity of functions to sustain ecosystem services may be more important than certain species' presence, *but they caution that this is an area where further research is needed*. Indeed, recent work provides empirical evidence for the significance of soil biodiversity for valuing ecosystem multifunctionality (Scherzinger et al. 2024).

Actions to fill gaps in the economic valuation of soil biodiversity

- Identify impacts on soil biodiversity that will have economic value, either from the natural capital value of the resilience and insurance values to future disturbances
- Identify socio-economic drivers of soil biodiversity in planning activities
- Foster interdisciplinary actions between economist and soil biodiversity research communities
- Increase research on how values can be used in conservation and management of land use

Bottlenecks to filling knowledge gaps in the economic valuation of soil biodiversity

The barriers to efficient economic valuation of soil biodiversity in response to management or conservation actions lies mainly in the gap between economic sciences and the soil biodiversity science. It is the lack of knowledge of the community of soil organisms ("who is there") and functions of these ("what are they doing") and how this connects to the valuation of the soils to different agents, e.g. land owners, society, and thus each depends on the user (Jónsson and Davíðsdóttir 2016) and their objective(s) (van der Putten et al. 2012, Pascual et al. 2015). Valuations that are not done with a clear objective and/or known recipient of the valuation will arrive at values of estimated ecosystem services that does not provide the necessary information to change a management or a policy (Bartkowski et al. 2020)

Identifying the costs of losing soil biodiversity and its services is difficult because service levels are realized over different spatial and temporal scales (Pascual et al. 2015, Jónsson and Davíðsdóttir 2016, Bartkowski et al. 2020) due

DOI: 10.5281/zenodo.17430539

to climatic gradients, soil organismal ecologies, and the change in weather and climatic condition (Scherzinger et al. 2024).

3.1.3 Conservation and restoration methods

What conservation methods protect soil biodiversity? Since conservation management and site selection have typically not considered soil biodiversity and its ecosystem functions, it is still unclear how current conservation affects soil biodiversity and how to adjust current conservation and restoration practices to positively impact soil biodiversity across the EU and regionally. The means of protection (e.g. creating protected areas, use of integrated management) can be applied to conserve soil biodiversity as mentioned above, protected areas are chosen based on varying desired outcomes, both ecological and cultural (Boitani et al. 2008, IUCN Standards and Petitions Committee 2024), and typically not for soil biodiversity conservation (Ciobanu et al. 2019, Zeiss et al. 2022). Rare species protection of soil organisms is atypical, because knowledge of specific species' abundances and distributions are, for the most part, lacking (Phillips et al. 2017, Karam-Gemael et al. 2020). Though examples exist on Earthworm species diversity and their conservation status (Stojanović et al. 2008), the distribution of species is often caused by trade-offs in life history;, and with changing environmental conditions the risks of extinctions increase (Jousset et al. 2017). Thus, we can expect both natural and anthropogenic processes driving the change of species spatial and temporal distribution in soil (Phillips et al. 2020, Patoine et al. 2022).

Regions across Europe must be evaluated for the objectives of conservation and what specific soil communities and associated functions they can support. Globally, areas that may rank highly in one ecological dimension, such as species richness, do not always have the highest functionality (Guerra et al. 2022). This suggests that potential sites for conservation are not equal, nor can they be treated similarly, when evaluating potential areas to conserve and what restoration/conservation practices are effective when targeting soil biodiversity. Abiotic conditions known to affect biodiversity have a large potential to host and conserve a diverse community of biota as shown for certain regions across Europe, such as Ireland, Slovenia, and Sweden (Aksoy et al. 2017).

Effective evaluation of current conservation and restoration practices requires knowledge of biotic/abiotic relationship complexities, including effects of land-use and human pressure to interpret the evaluation of current practices but what we know is that with sustainable land use, soil biodiversity can be supported (Phillips et al. 2024). General management options could be "scaled-up" (Barrios et al. 2023) as considering ecosystem functions during assessment of site-scale measures to management efficacy can vastly improve conservation of soil biodiversity at broader, social scales i.e. landscape scale (Ciobanu et al. 2019, Zeiss et al. 2022). Improvement and use of long- term studies and experiments that focus on specific techniques needs further research, such as dead wood management in forests and encouraging heterogeneous soil habitats through diversifying plant species (Eisenhauer et al. 2013, Eisenhauer 2016, Scherber et al. 2010). In addition, there is increasing evidence that suggests that landscape diversification benefits soil biodiversity (e.g. Vahter et al. 2022).

Protecting soil biodiversity in a nature conservation framework has the potential to not only preserve the biotic community, but also the ecosystem functions provided. Active restoration and conservation require attention to the complexity of species diversity and other biodiversity facets (e.g. size variation, life history traits) (Eisenhauer et al. 2021, Guerra et al. 2022, Guerra et al. 2024) as well as a diversity of functions (Nielsen et al. 2011). Maintenance of species richness, community composition, and ecosystem functions are not often synonymous, and investigations into a trait-based approach to soil biodiversity conservation and restoration are largely lacking (Guerra et al. 2022). Assessments of soil biodiversity and its associated functions are known from only 0.3% of sampled sites (Guerra et al. 2020) and, this lack of data results in an incomplete picture of how identified taxonomic units are functioning in soils and how to affect them through management. Auclerc et al.

DOI: 10.5281/zenodo.17430539

(2022) summarised the importance of functional trait approaches to restoration with soil invertebrates but also detailed critical knowledge gaps. These include a lack of knowledge of:

- trait-based techniques for restoration of soil biodiversity
- the functions invertebrates play in the ecosystems
- representation of functional data in current trait-based databases
- relationships of ecosystem function to traits

Actions to fill gaps in soil biodiversity conservation and restoration methods

- Explore and promote land management strategies improving soil biodiversity.
- Evaluate current and future policy instruments and develop decision frameworks and guidelines for conservation of soil species biodiversity
- Address data gaps and enhance soil biodiversity indicators
- Support stakeholders' networks and engagement in soil policy and land use management.

Bottlenecks to filling knowledge gaps in soil biodiversity conservation and restoration methods

Challenges and bottlenecks to filling these gaps in knowledge to conserve soil biota require an expansion of toolsets and innovative approaches to tackle the predictions of diversity at sites. In brief, the bottlenecks and the importance of advancing the science of soil-dwelling taxa need information on how to effectively conserve and restore soil life. These include:

1. the barriers to discovering and describing the numerous and diverse, yet unknown, taxa in soils,
2. the lack of understanding of life histories and functions of a large part of the soil organisms and how this drives their distributions,
3. the threats to soil biodiversity, such as invasive species and extinction risks.

3.2 Prioritized knowledge gaps

3.2.1 Harmonised conservation frameworks

Conservation frameworks are employed for different purposes and include not only species richness but also cultural, aesthetic, ecological aspects, as well as ecosystem services. In contrast to aboveground life, which is more easily observed and vastly more investigated, the richness and ecosystem functions of soil invertebrate and microbial taxa are still in need of clarification (Eisenhauer et al. 2019). This leads to the question, what species/taxa are in need for conservation, and what frameworks could be used to secure the efficient conservation of soil biodiversity? While the overall diversity (species richness) of taxa in soil is huge, largely unknown, and important in and of itself, the functional aspects of soil faunal and microbial life cannot be lost in the process of protecting taxonomic diversity (Phillips et al. 2020). It is not clear for example, whether aspects of soil biodiversity can be related to aboveground ecosystems' conservation status and conservation frameworks (Cameron et al. 2018, Zeiss et al. 2022). Thus, new research is needed to investigate if current (aboveground) conservation frameworks can be used for soil biodiversity or specific frameworks for soil biodiversity conservation are needed. As with otherall conservation frameworks, clear goals and objectives should be set, which should focus on both diversity of taxa and diversity of functions/services provided. Policies and legal foundations are needed for the efficient implementation of the conservation framework. These should be implemented at several scales, from the local to the national, regional or global scale, and complement each other.

Stakeholder identification and engagement is also a significant step towards conservation efficiency at any level. Additionally, Tthere is a lack a unified definition of soil biodiversity to use as a basis for policy development and regulatory measures (Rillig et al. 2019, FAO et al. 2021).

DOI: 10.5281/zenodo.17430539

Finally, the conservation framework should encompass monitoring requirements and selection of soil indicators, thus the previous knowledge gaps on monitoring and standardisation methods needs to be aligned to the frameworks that are used in actions to conserve soil biodiversity.

3.2.2 Need for public awareness of soil biodiversity

Education and awareness-raising of the importance of soil biodiversity to the provision of ecosystem functions and services is important to adjust perceptions regarding the protection of soil life. Many of the challenges of communicating the importance and need for the protection of soil biodiversity are similar to other issues in global environmental science education. Thus, this knowledge gap will be linked to the Think Ttank on Soil LI iteracy, which addresses knowledge gaps regarding public awareness. The knowledge gap is here to see the transformation of change and when to make use of public awareness of soil biodiversity. A thorough understanding of the problem, and solution is needed, to translate understanding to a change in behavior in order to gain public support for protection of soil life and its functions.

How can communication of soil biodiversity be enhanced? One way to do this is to focus on the local context of soil conservation to a particular audience (i.e. urban, agricultural, land manager/steward) – the "why-YOU-should-care" approach (Moscatelli and Marinari 2024). Another is to use methods in media communications rather than soil science to reach the public since scientific jargon can cause a feeling of disaffectedness. Through artistic means we can also engage the wider public in a way to evoke caring about soil and soil life (Toland and Wessolek 2010).

In 2009, the JRC, with support from the European Soil Bureau Network, established a Working Group on "Soil Awareness and Education" to establish an action plan for development of initiatives to raise awareness of the importance of soil and soil biodiversity across the European society. Subsequently, the JRC initiated a Working Group that now has been broadened to support European Soil Partnership (ESP) Pillar 2, which targets soil awareness and education.

3.2.3 Need for implementation of effective soil biodiversity conservation strategies

Conservation strategies involve the planning and implementation of protection of a species or area as well as specific methods. While we have a lack of knowledge of what an effective nature conservation strategy looks like, there are inter- and transdisciplinary ways of implementing the integration of soil biodiversity into the decision-making process of conservation professionals (Fig. 4, Parker 2010). This requires the interactions and cooperation between conservation planners and soil ecologists.

For conservation and environmental planners, the scale of conservation strategies is typicallyat the landscape level, but, for the majority of soil-dwelling species, interactions happen at the scale of micrometer to over hundreds of meters (Hedlund et al. 2004). The challenges of scaling-up monitoring and conservation schemes that are representative of the heterogeneity and scale of interaction of soil biodiversity remains a main frontier for both conservation strategy development and soil ecology and is a relevant knowledge gap. Knowledge from previous assessment and strategies for conservation show that there has been a bias towards large soil taxa and a lack of soil microbes in previous assessments and strategies (Klironomos 2002). In the last 10 years, one can argue that this bias has reversed with the relative ease of modern molecular techniques intended to investigate microorganisms in water and soil substrates.

This knowledge gaps is highly integrated into the already mentioned knowledge gap on conservation frameworks (see 3.1.1) and research is needed to work out how both frameworks and strategies can be further developed into conservation of biodiversity.

DOI: 10.5281/zenodo.17430539

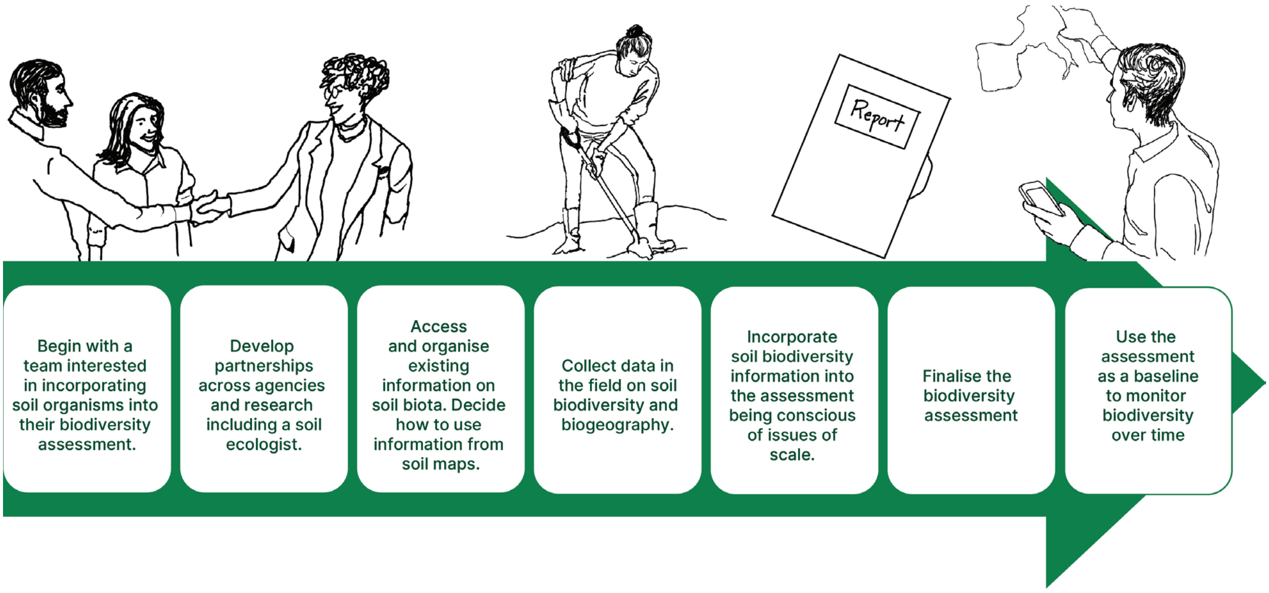

Figure 4. Suggested steps to incorporate soil biodiversity into overall biodiversity assessments for the purposes of conservation strategies. Redrawn from Parker (2010).

3.2.4 Lack of minimum dataset to index soil biodiversity

While chemical and physical parameters can be measured easily in routine procedures, biological parameters are more difficult to measure, more costly and require special expertise. Time and financial limitations are significant barriers for the analysis of numerous parameters in each soil sample (O'Sullivan et al. 2017). The choice of relevant soil parameters and interpretation of measurements are not straightforward and often several parameters show collinearity, thus some are redundant (Lima et al. 2013). Hence, it is not anticipated that all possible biological parameters would be measured in a soil sample (especially at large scales), nor is it self-evident that the ones selected for measurement would also be the most informative ones.

The concept of a Minimum Data Set (MDS) for soil quality assessment, which would be a set of selected key physical, chemical, and biological indicators, was propsed in work with human health by Doran and Parkin (2015). The concept of MDS has also been used successfully in the assessment of water quality (Ingvertsen et al. 2011). But is it possible to monitor soil for the conservation of soil biodiversity with an MDS? The typical biological parameters measured are those for which the researcher has interest and expertise (e.g. focusing on one group of organisms, such as earthworms, microbes etc.). Molecular tools have provided new opportunities for the possible inclusion of biological aspects into MDS selection, but their informativeness has boundaries and additional conventional or morphological methods are needed to complete the necessary input.

The MDS selection should cover criteria such as integrating soil processes, consistency and comparability across different studies and management systems, sensitivity to management and climatic changes (Doran and Parkin 2015). For soil biodiversity other aspects, like the soil as a habitat, have to be considered as well (Baveye et al. 2016). Methodological transparency and simplicity would be essential for enabling the broad adoption and application of the MDS selection. Among soil parameters/indicators, biological ones are considered more informative but are not always included in MDS selections (Bünemann et al. 2018). In systematic, large scale soil monitoring projects, the MDS of parameters typically includes chemical and physical parameters, usually and, lately, some biological ones (e.g. LUCAS inventories from 2018 and 2021). Several biological indicators have been proposed in literature as being efficient in denot-

DOI: 10.5281/zenodo.17430539

ing a wider biodiversity range (e.g. in Ritz et al. 2009). Using a subset of those for an MDS would provide merit in large- scale monitoring projects for soil biodiversity conservation, as this would reduce cost and labor. However, standard operating procedures (SOPs) are essential for this work at a large scale. This, in turn, requires collaboration among different experts and setting common scopes.

3.2.5 Lack in knowledge of specific threats to soil biodiversity

The current knowledge on threats and, especially, extinction risks for soil-dwelling biota is little and inconsistent, but vital to knowing where and how to conserve this diverse biotic group. However, the vulnerability of soil invertebrate and microbial organisms, including rare species, is almost entirely unknown and little progress has been made (Decaëns et al. 2008). Bottlenecks to the conservation of soil organisms include knowledge of identifying very rare/threatened, endemic, and vulnerable species and their habitats for protection (Veresoglou et al. 2015).

To protect vulnerable species or groups, there is a need to identify and have threatened species recognized, requiring knowledge of the species (or group) and its functional role, especially in the case of species that are highly sensitive to climate shift, invasion of exotic species, etc. Moreover, standardised assessment criterion for rare or threatened taxa across the EU is necessary for European and regional EU regional conservation efforts of conservation (van der Putten et al. 2023). With these standards, we could potentially identify the taxa at risk, create a preliminary list of what species/OTUs are threatened, and identify conservation practices, concrete management options, and potential sites for conservation. This is critical to predict the fate of soil organisms under global change and ensure their conservation.

A corollary to the identification of rare, threatened, and endemic species is, what are the criteria to designate something as invasive with regards to soil organisms? This has not been taken into consideration, primarily, because the directionality of invasions in soils is difficult to determine, and we are unaware of the identity of most local and invasive soil taxa. It is also unknown what environmental, or economic damage ‘invasive’ organisms can cause to soils and ecosystems, unlike similar studies in, for example, agricultural settings. The two barriers to finding out this information are that (1) there is little way to track invasion or origin of a present organism, and (2) there are no conceptual models to think about what a species is in the way plant or animal species are conceptualized, especially for microbes.

3.2.6 Lack in knowledge of species taxonomic identity and ecology

Many soil taxa are unknown to science and awaiting description (Orgiazzi et al. 2016) because:

1. Soil fauna and microbes are often cryptic and difficult to observe without disturbing their functioning and habitat, and the variance in the diversity of these communities is significant over just millimetres (Rillig et al. 2015).
2. Microbial taxa are difficult, sometimes impossible, to isolate and culture with our current methodologies. This is compounded by the differences in methods necessary to detect and quantify different soil organisms due to heterogeneity in their ecologies (ranging from water-related to truly terrestrial species), size classes (ranging from microbes to megafauna), and distribution patterns (Decaëns 2010, White et al. 2020, Eisenhauer et al. 2021).
3. Specialised taxonomic expertise is needed to identify invertebrate species within groups of soil animals. Expertise in many soil fauna groups is rare, leading to a perpetual cycle of infrequent opportunities for knowledge transfer and a dwindling body of experts.

Filling gaps in the taxonomic, as well as functional, information of soil biota communities, starting with those in already vulnerable ecosystems is of key importance. Knowledge is partly lacking on impact of extreme oscillations in precipitation

DOI: 10.5281/zenodo.17430539

and temperature. It is also critical to provide the foundation to monitor the influence of soil invasive species, both for conservation of diversity but also for the functioning and stability of our ecosystems.

Studies of ecology and life histories of soil-dwelling species are time-consuming and detail-oriented undertakings are necessary to understand their ecosystem functions and effects on other life, yet they are often considered not innovative enough to be funded. Current knowledge in invertebrate ecology is based on manipulative landscape experiments and some direct observation and mesocosm experiments, the latter two of which are rare research approaches in ecology, but common in biological control. In microbial research, the current methods include molecular methods for identification (i.e. metabarcoding, "shotgun" approaches), with substantially fewer studies on the functional genes that reveal what different microbes digest and release.

3.2.7 Lack in knowledge of spatial and temporal distribution of soil biodiversity

We lack critical information on most soil taxa, their habitats and what drives their distributions to be able to understand how and where conservation can be achieved for different taxonomic groups (Cameron et al. 2019). This includes the drivers of community dissimilarity in soil taxa across ecosystems, along with their uniqueness (e.g., endemic species, specialisation for given habitats). For instance, while disturbed habitats can show high species richness and total densities, these are often caused by generalist species, leading to a homogenization of soil biodiversity and loss of diversity at the landscape scale in a region or country (Gossner et al. 2016, Delgado-Baquerizo et al. 2021, Guerra et al. 2021a, Banerjee et al. 2024). Recent work revealed the ubiquity of complex interactions between multiple co-occurring environmental drivers that could affect distributions or evolutionary tactics (Rillig et al. 2019), yet these are poorly studied. These complexities, including effects of land-use and human pressures, are needed in an integrated evaluation of current practices. Extrapolating conclusions from agricultural research that investigat eding increasing soil biodiversity for increased ecosystem function can be a starting point for developing knowledge of distribution patterns. Long- term studies and experiments focusing on specific techniques, such as dead wood management in forests, recognition of trees as "hot spots" of soil biological activity and encouraging heterogeneous soil habitat through diversification of plant species (Eisenhauer et al. 2018) are needed to understand their direct and indirect effects on soil biodiversity.

Current understanding of distributional patterns is based on expert knowledge, observational data from landscape gradient studies, and/or available records in museum collections, but these vary in utility. One common issue is thate lack of necessary environmental and climate metadata to associate taxa to habitat characteristics is missing from publications and, essentially, non-existent in museum records (Gotelli et al. 2023). Experimental research on the response of soil taxa presence and diversity to environmental predictors is patchy (Phillips et al. 2024), biased towards unrealistic levels of edaphic parameters change, and unrepresentative for some climates, such as the tropics (Cameron et al. 2018, Guerra et al. 2020), and not directly comparable across ecosystems.

The overall lack of abundance and distribution baselines and possible thresholds for soil organisms comparable to those for above-ground organisms do not exist though they are urgently called for by policy (European Environment Agency 2023). "Red Listing" of soil invertebrate organisms is rare (Phillips et al. 2017, Mueller et al. 2022) because, for one reason, typical criteria for listing, such as "population size" in a region or country, are inappropriate for organisms in substrate such as soil. Few studies have incorporated IUCN criteria (i.e. IUCN Standards and Petitions Committee 2024) for identifying threatened or endangered soil species (Marchán and Domínguez 2022, Salako et al. 2023). However, this necessitates answers to some fundamental, yet wholly uninvestigated questions: What defines rarity for soil taxa? How appropriate for the myriad of soil taxa are local abundance, habitat specificity, and/or geographical distribution in determining rarity? How do we determine susceptibility to extinction for soil biota?

DOI: 10.5281/zenodo.17430539

Table 4. Overview of knowledge gaps (KGs) for effective nature conservation of soil biodiversity (SB), their types, actions by which these KGs may be filled, and barriers (bottlenecks) to previous attempts to fill these gaps. Type of KG: KDG - Knowledge Development Gap; KAG - Knowledge Application Gap. Action: (R) - Research; (I) - Innovation. All knowledge gaps apply across multiple sectors (i.e. agriculture, forest, urban and industrial and/or nature).

Knowledge gap	Short description	Type of KG	Action	Bottlenecks	Time-frame
Standardisation of SB and ecosystem function monitoring methods	Standardised methods of field data collection are needed to provide baselines and monitor trends in the abundance and diversity of soil biota and its functions.	KDG	- Harmonisation and standardisation of methods and data management (R, I) - Develop and enhance soil biodiversity indicators (R, I) - Identify examples of standard and easy to measure biodiversity indicators (R) - Develop a comprehensive information system of soil biodiversity (R, I)	- Lack of unified network of sharing methods hinders standardisation of monitoring methods - Complicated to develop SB indicators that work for all climatic conditions or soil types	Short-term
Economic valuation of SB	A common, comprehensive framework is lacking for economic valuation of SB. Studies on evaluations of SB are lacking	KDG	- Identify impact on soil properties that will have economic value (R) - Identify socio-economic drivers of soil functions and services in planning activities (R) - Foster interdisciplinary actions between economist and SB research communities (I) - Increase research on how values can be used conservation and management (R)	- Disconnection between economic sciences and SB sciences hinders efficient valuation of SB in response to management or conservation actions	Short-term toMid-term
Conservation and restoration methods	Current conservation and restoration methods' impact on SB is unclear and it is also unclear how to adjust them so that they positively affect soil biodiversity	KDG	- Explore and promote sustainable land management strategies (R,I) - Evaluate current and future policy instruments and develop decision frameworks and guidelines for conservation of soil species (R) - Address data gaps in soil health, improvement measures and enhance SB indicators (R,I) - Support stakeholders' networks and engagement in soil policy and land use management (I)	- Unknown species and taxa in soil hinders conservation actions and strategies - Lack of understanding of life histories and functions of many soil organisms and how this drives their distribution hinders conservation actions and strategies - Knowledge on threats to SB, and extinction risks, is lacking, which hinders conservation actions and strategies	Short-term
Harmonised conservation frameworks	How can frameworks be used to secure efficient conservation of SB. Can we use existing framework or do we need a new framework?	KDG	- Establish framework for conservation of soil biodiversity and functions (R,I) - Evaluate current and future policy instruments, advocate regional knowledge adoption strategies and integrate SB into planning activities (R,I)	- Lack of policy targets for conservation and restoration hinders conservation	Short-term
Need for public awareness of SB	Effective ways of communicating about conservation of SB are lacking. It is necessary to gain public support for protection of soil life and its functions	KAG, KDG	- Stakeholders' learning networks, collaboration and early engagement in soil policy and management development (R,I) - Social research on the best communication methods for SB awareness (R)	- Disconnection between social sciences and SB sciences hinders social research on the best communication methods for SB awareness	Short-term

DOI: 10.5281/zenodo.17430539

Knowledge gap	Short description	Type of KG	Action	Bottlenecks	Time-frame
Need for implementation of effective SB conservation strategies	Knowledge of effective nature conservation strategies for SB is lacking. Inter- and transdisciplinary ways of implementing the integration of SB into decision making process of conservation professionals is needed	KAG	- Stakeholders' learning networks and engagement in soil policy and management development (R,I) - Develop guidelines for conservation of soil species and integrate SB conservation into planning activities (R,I)	- The scale of conservation strategies focuses on landscape level, but most soil organism interactions occur at very small scales causes discrepancies in actions	Mid-term
Lack of minimum dataset to index SB	A minimum dataset to index SB is lacking. Would it be possible to monitor soil for the conservation of SB with the concept of Minimum Dataset?	KDG	- Methods development/ improvement (R) - Develop understanding of relevant biological soil parameters and interpretation of measurements for conservation of SB (R) - Collaboration network for different experts (I)	- Difficulty and cost of measuring biological parameters causes uncertain predictions due to low replication	Mid-term
Lack in knowledge of specific threats to SB	Current knowledge on threats and extinction risks for soil organisms is little and inconsistent. Vulnerability of most soil organisms, including rare species, is almost entirely unknown	KDG	- Red list development (R) - Develop criteria for invasive species designation (R) - Identification and monitoring of threats impacts (R) - Standardised assessment and risk analysis for policy guidance (R,I)	- Difficulty of tracking origin of a present soil organism causes uncertainties regarding invasive species - Unclear species concept hinders concervation actions to mitigate threats to SB	Short-term
Lack in knowledge of species taxonomic identity and ecology	Filling gaps in taxonomic and functional information on soil biota communities is needed to provide the foundation for monitoring and conserving soil biodiversity	KDG	- Capacity building (training in taxonomy) - Methods development/ improvement (R) - Develop a unified definition of SB for policy development (R) - High resolution sampling and monitoring (R)	- Lack of taxonomic expertise hinders identification of species - Unclear species concept hinders identification of species	Short-term
Lack in knowledge of spatial and temporal distribution of SB	Information on the spatial and temporal distribution of most soil taxa and what drives the distribution is lacking. This is needed for understanding of how and where conservation can be achieved for different taxonomic groups	KDG	- High resolution sampling and monitoring (R) - Develop a comprehensive understanding of what drivers affect distribution of soil organisms (R) - Red list development (R) - Develop a definition for rarity for soil taxa (R)	- Unclear species concept hinders identification of species - Lack of taxonomic expertise hinders identification of species	Short-term
Data storage & Digitalisation needs	Data is generally stored with IPR regulations and not available for open access	KAG	- Develop a comprehensive information system of soil biodiversity (I)	- Lack of binding policy	
Improved predictive modelling	Predictive modelling needs improvement due to the small-scale heterogeneity of soil communities	KDG	- Methods development/ improvement (R)		

DOI: 10.5281/zenodo.17430539

3.3 Overview of knowledge gaps

Table 4 provides an overview of knowledge gaps (KGs) for effective nature conservation of soil biodiversity, their types, actions by which these KGs may be filled, and barriers (bottlenecks) to previous attempts to fill these gaps.

Conclusion

Conservation of soil biodiversity is a multifaceted process involving, what we expect will be, a multitude of approaches that will benefit the large-scale diversity of soil life across Europe as well as the needs and environments of the regions within Europe. Developing effective ways to conserve and monitor the trends in soil biodiversity across the complex functions of these communities is as important as the communities themselves and should be considered in developing plans for their protection.

Acknowledgements

We thank Dr Diana H. Wall for her contributions to the Nature Conservation of Soil Biodiversity Think Tank, this Outlook document, and her life-long commitment to sustainability, and soil biodiversity and ecosystem function science. We also thank the reviewers of this and previous document versions.

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DOI: 10.5281/zenodo.17430539

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Supplementary materials

Supplementary materials for "Outlook on the knowledge gaps to reduce land degradation in Europe"

Supplementary material 1

Table 2 Knowledge gaps

Author: Melpomeni Zoka

Data type: Table

			Sector						Actions			
Knowledge gap	Short description	Type of KG	Agriculture	Forest	Urban and industrial	Nature	Multiple	Bottlenecks	Action	Type of action	Priority	Timeframe
1. What are the most efficient and cost-effective Land Degradation prevention and restoration measures, incorporating an assessment of trade-offs between different land uses and pedo-climatic zones?	There is a critical gap in identifying cost-effective and efficient land degradation prevention and restoration measures that account for trade-offs between land uses and pedo-climatic zones. While promising practices like biochar and organic matter management are explored (Maroušek and Trakal 2022, Kalu et al. 2022), research mainly focuses on agricultural soils, neglecting urban and other land types (Löbmann et al. 2022). Studies like Bardgett et al. (2021) and Silva et al. (2023) highlight the need for standardized assessments, participatory models, and better resource allocation to address challenges and optimize restoration efforts across diverse contexts.	Knowledge Development Gap	X	X	X	X	X	1, 2, 3, 4, 5, 8, 9, 10, 11, 13, 14, 15, 16, 26	1, 2, 3, 5, 6, 10, 11, 12, 14, 15	Research & Innovation	High	Short-term=5 y
2. Lack of thorough understanding of the interactions between Land Degradation and Ecosystem Services.	A significant knowledge gap exists in understanding the interactions between land degradation and ecosystem services (ES), which hinders effective policy-making and sustainable management strategies. Key limitations include data scarcity and measurement challenges, especially in assessing soil health and ES delivery (Petrosillo et al. 2023a). Remote sensing has potential, but integrating it with field assessments remains difficult (Prokop 2020, de Oliveira et al. 2022). Additionally, cultural ecosystem services (CES) are often overlooked, with a lack of frameworks to quantify social, cultural, and psychological factors that drive engagement with nature (Jones et al. 2021). Furthermore, limited research on soil biodiversity and the integration of ES into land use policies and socio-economic contexts remain major barriers (Oberreich et al. 2024, Wei et al. 2018). Addressing these gaps, particularly through improved data collection and policy integration, is crucial for advancing sustainable land management and ecosystem service delivery in the face of land degradation (UNCCD 2017, Mason et al. 2023).	Knowledge Development Gap	X	X	X	X	X	1, 2, 3, 4, 5, 8, 9, 11, 13, 16, 17, 22, 23, 25	1, 2, 6, 10, 11, 12, 14, 15	Research & Innovation	High	Midterm= 10y

DOI: 10.5281/zenodo.17430539

Knowledge gap	Short description	Type of KG	Sector					Bottlenecks	Actions		Priority	Timeframe
			Agriculture	Forest	Urban and industrial	Nature	Multiple		Action	Type of action		
3. What are the historical, current and future social and economic interactions with Land Degradation?	Land degradation significantly impacts both social and economic spheres, but several knowledge gaps persist in understanding its historical, current, and future interactions. Socially, while the immediate effects on agricultural productivity and rural livelihoods are studied, the broader societal consequences—such as health, migration, and the role of indigenous knowledge—remain poorly understood (Johnson et al. 2024, IPBES 2018). There is also a need to explore the socio-economic benefits of sustainable land management practices in diverse EU contexts (Löbmann et al. 2022a, Visser et al. 2019). Economically, land degradation leads to substantial costs, particularly in agriculture, with the EU losing billions annually (Panagos et al. 2018). However, there are gaps in economic assessments of soil protection measures, especially at the farm level, and in accounting for off-site impacts like soil erosion (Tepes et al. 2021, Kubiszewski et al. 2013). More localized and participatory research, considering both social and economic factors, is crucial for developing effective policies and achieving land degradation neutrality in the EU (Knierim et al. 2015, IPCC 2019).	Knowledge Development Gap	X	X	X	X	X	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 16, 17, 18, 20, 21, 22, 24, 26, 27	All actions except for 8	Research & Innovation	High	Midterm= 10y
4. Lack of comprehensive understanding of Land Degradation (effects and drivers)	There is a lack of comprehensive understanding regarding the causes, processes, and impacts of land degradation across various regions and soil types (Reynolds et al. 2007, Saljnikov et al. 2022, Daliakopoulos et al. 2016). Challenges arise from differing perspectives on land degradation, limited studies on soil compaction, and difficulties in understanding the complex interactions of Soil Organic Matter (SOM) fractions (Gianoli et al. 2023). Although case studies exist, applying these findings on a continental scale is challenging, as detailed, site-specific examinations are required (Gianoli et al. 2023). Gaps remain in understanding soil compaction impacts and SOM interactions, particularly regarding aboveground and belowground biota (Orgiazzi and Panagos 2018) and the effects of drivers on SOM accumulation and decomposition (Jia et al. 2019). More research is needed to address these gaps and improve our understanding of land degradation's complex dynamics.	Knowledge Development Gap	X	X	X	X	X	1, 2, 3, 5, 8, 9, 11, 13, 16, 20, 23, 25	1, 2, 6, 10, 11, 12, 14, 15	Research & Innovation	Moderate	Long-term>10y
5. How can we enhance regional planning regarding reducing Land Degradation?	Enhancing regional planning to reduce land degradation is hindered by fragmented policies and lack of coordination among stakeholders (Saik et al. 2024). Improved data collection and spatial planning tools are needed to assess risks and align LDN efforts with climate and economic goals (Oliveira et al. 2018, Briassoulis 2019). The integration of ecosystem services into land-use planning remains underdeveloped (Zhang et al. 2022, Cowie et al. 2018), and strategic spatial planning must be expanded to include concrete strategies for land restoration (Oliveira et al. 2018). Clear objectives and the involvement of all sectors are essential for effective land use management.	Knowledge Application Gap			X			1, 2, 3, 4, 5, 6, 7, 9, 10, 11, 16, 24, 27	1, 2, 5, 6, 11	Research & Innovation	Moderate	Midterm= 10y

DOI: 10.5281/zenodo.17430539

Knowledge gap	Short description	Type of KG	Sector					Bottlenecks	Actions			
			Agriculture	Forest	Urban and industrial	Nature	Multiple		Action	Type of action	Priority	Timeframe
6. Lack of Land Degradation related data and limited monitoring at different scales	Accurate, high-resolution data on land degradation (LD) is essential for developing effective policies and solutions, but significant gaps exist across spatial and temporal scales (European Commission 2019a, European Commission 2020a). Limited data on soil health, land cover, and crop management practices complicates the monitoring and restoration of land (Panagos et al. 2020, Manna et al. 2024). Additionally, challenges in differentiating between drivers and processes of degradation hinder the development of precise risk projections (von Keyserlingk et al. 2023, Akbari et al. 2016). The lack of a consistent framework for integrating temporal dynamics further limits adaptive management strategies (Masoudi and Jokar 2018, Martínez-Valderrama et al. 2020). Therefore, improving data collection and fostering research are critical to inform effective land management and policymaking.	Knowledge Development Gap	X	X	X	X	X	1, 2, 3, 5, 6, 8, 9, 11, 13, 16, 20, 22, 23, 25, 26	1, 2, 6, 11, 12, 14	Research & Innovation	Moderate	Short-term=5 y
7. How do we support farmers to make the turning point towards sustainable land and soil management soil practices?	Farmers often rely on practices like ploughing, which can degrade soil and reduce long-term yields (Quinton et al. 2022). Despite recognizing the challenges of such practices, many lack the knowledge to transition to sustainable land and soil management. Tillage, common globally, contributes to soil thinning, increased erosion, and reduced productivity, especially on sloped land (Quinton et al. 2022). To support this transition, farmers need improved knowledge, training, and access to tools like business models that highlight the benefits of non-tillage practices. Additionally, providing reliable market data can help farmers navigate economic fluctuations, enabling them to adopt sustainable practices that enhance both productivity and soil health.	Knowledge Development Gap	X	X				1, 2, 3, 4, 5, 8-27	All actions	Research & Innovation	Moderate	Short-term=5 y
8. Limited mitigation Land Degradation strategies	Further research is needed to optimize soil management practices and strategies that mitigate and prevent land degradation (Vanino et al. 2023). Emphasis should be placed on developing innovative, sustainable practices tailored to different regions and scales (European Commission 2020a, FAO 2015). Haregeweyn et al. (2023) stress the need for systematic methodologies to advance and adopt suitable Sustainable Land Management (SLM) practices across diverse conditions (Giger et al. 2018, Gonzalez-Roglich et al. 2019, Liniger et al. 2019). Challenges such as insufficient field-level monitoring and limited land user involvement in SLM tasks (Liniger et al. 2019) must be addressed. Moreover, demonstrating both on- and off-site impacts and assessing the full costs and benefits of SLM practices is essential for informed decision-making (Giger et al. 2018, Schwilch et al. 2014).	Knowledge Application Gap	X	X	X	X	X	1, 2, 3, 5, 8, 9, 11, 13, 15, 16, 20, 22, 23, 27	1, 2, 3, 6, 11, 12, 14	Research & Innovation	Moderate	Midterm= 10y
9. How do we educate and inform the population more effectively about the value of natural resources, including soil?	Educating and engaging the public about the value of natural resources, such as soil, is crucial for sustainable land management and environmental conservation. Effective engagement requires meaningful dialogue between science, policy, and society, as seen in recent EU initiatives that involve citizens in biodiversity policy development (Varumo et al. 2020). Tools like online science cafés and iterative communication processes help foster public participation and influence policy on complex issues like soil degradation. Traditional education methods are insufficient, so education for sustainability must be collaborative, involving multiple sectors and levels of governance, particularly schools and educational institutions (Wals and Benavot 2017). This inclusive approach ensures that long-term environmental concerns, including soil health, are incorporated into decision-making processes.	Knowledge Application Gap					X	4, 5, 10, 12, 13, 17, 20, 27	4, 5, 7, 13	Research & Innovation	Moderate	Short-term=5 y

DOI: 10.5281/zenodo.17430539

			Sector						Actions			
Knowledge gap	Short description	Type of KG	Agriculture	Forest	Urban and industrial	Nature	Multiple	Bottlenecks	Action	Type of action	Priority	Timeframe
10. Is the concept of Land Degradation Neutrality enough to ensure healthy land and soils in the future?	While Land Degradation Neutrality (LDN) provides a promising framework to address land degradation, it is not sufficient by itself to ensure healthy land and soils in the future. LDN promotes a balanced approach by integrating both degradation and restoration efforts, but challenges remain in applying it at local and regional scales, especially in regions with fragmented land ownership and insecure land tenure (Feng et al. 2022, Mikhailova et al. 2024). Moreover, LDN should be evaluated with consideration of soil types and land-use practices, as well as the socio-economic context, particularly in areas with land fragmentation and insecure tenure (Sutton et al. 2016, FAO 2021). To effectively combat land degradation, LDN must be integrated into broader land-use policies that address these issues and incorporate social and financial dimensions (Mikhailova et al. 2024). Continued research and policy development are essential to close knowledge gaps and improve LDN's effectiveness globally.	Knowledge Development Gap	X	X	X	X	X	2, 3, 5, 6, 7, 8, 11, 15, 16, 25, 26	1, 2, 4, 5, 9, 13	Research & Innovation	Moderate	Short-term=5 y
11. What are the historical, current and future climate change interactions with LD in the EU	The interactions between Land Degradation (LD) and climate change remain poorly understood, with significant gaps in knowledge about their feedback mechanisms and how climatic factors influence land degradation (European Commission 2015, IPCC 2001, Odebiri et al. 2023). Key questions, such as which variables are crucial for monitoring these interactions, and how climate change either mitigates or accelerates land degradation, remain unanswered (Reed and Stringer 2016). While research often focuses on the impacts of climate change on agriculture, it overlooks other sectors like livestock, forest farming, and pests, which also contribute to land degradation (Farooq et al. 2022). To address these gaps, further research is needed to explore how climate change affects LD and how degraded land might contribute to climate mitigation efforts.	Knowledge Development Gap	X	X	X	X	X	1, 2, 3, 5, 8, 9, 11, 13, 18, 19, 20, 25	1, 2, 6, 8, 10, 11, 12, 14, 15	Research & Innovation	Low	Long-term>10y
12. What are the historical, current and future biodiversity loss interactions with LD in the EU	Land Degradation and biodiversity loss are interlinked processes. Despite this fact, there are several limitations in understanding the causal relationships and feedback loops between biodiversity loss and land degradation. Examples of relevant knowledge gaps can be found in the effects of climate adaptation options on soil's role as a habotat and genetic reservoir. More precisely, according to the study of Hamidov et. al., 2018 (Hamidov et al. 2018), among the 20 EU case studies that they examined regarding the impacts of climate change adaption options on soil functions, solely a few consider the impacts on soil biodiversity. The evident neglect of soil biodiversity issues in the majority of case studies contradicts the growing recognition of the crucial functional role of soil organisms in soil processes (Cluzeau et al. 2012). This represents a significant knowledge gap that requires attention in future research endeavors (Hamidov et al. 2018). Additionally, there is a need for standardized, comprehensive approaches for measuring the compaction, diversity, and function of soil biota (Thiele et al. 2020, Saljnikov et al. 2022).	Knowledge Development Gap	X	X	X	X	X	1, 2, 3, 5, 8, 9, 11, 13, 16, 20, 22, 25	1, 2, 6, 11, 12, 14, 15	Research & Innovation	Low	Midterm= 10y

DOI: 10.5281/zenodo.17430539

			Sector						Actions			
Knowledge gap	Short description	Type of KG	Agriculture	Forest	Urban and industrial	Nature	Multiple	Bottlenecks	Action	Type of action	Priority	Timeframe
13. Absence of well-established and interlinked policies and legislation concerning LD and its components	Lack of well-established and/or Land Degradation-related policy frameworks lead to unclear guidelines for soil management, resulting in a lack of standardisation in R&I methodologies (European Environment Agency 2019, Guerra et al. 2016). While this can be mainly seen as a bottleneck, it can also be characterised as lack of knowledge when interlinkages between drivers affect the process of establishing clear policies. A relevant example refers to the study of Paleari, 2017 (Paleari 2017), where it was noted that despite the existence of several policies to address and regulate some soil threats, otheres, such as salinization, receive only limited consideration and lack a comprehensive framework for soil protection.	Knowledge Development Gap					X	1, 2, 5, 6, 7, 8, 9, 11, 16, 18, 24	2, 5	Research & Innovation	Low	Midterm= 10y
14. Knowledge gaps in the quantification of off-site Land Degradation effects and costs	The contemporary understanding of land degradation is marked by a significant gap in knowledge, particularly concerning the quantification of off-site effects and costs associated with Land Degradation (Saljnikov et al. 2022, Boardman et al. 2019). This refers to the impacts that extend beyond the immediate area of degradation and affect surrounding regions or ecosystems. The existing knowledge deficit in this specific aspect underscores the need for up-to-date research efforts to address and quantify these off-site effects and costs comprehensively.	Knowledge Development Gap					X	1, 2, 3, 5, 9, 11, 16, 23	1, 2, 6, 11, 12, 14, 15	Research & Innovation	Low	Midterm= 10y
15. Insufficient knowledge for accessing funds related to Land Degradation and soil projects and initiatives	Insufficient knowledge to navigate the administrative procedures for accessing funds related to Land Degradation and Soils (European Commission 2021c, EU Soil Observatory 2019). Are Land Degradation related funds and efforts sufficient to stop it?	Knowledge Application Gap					X	4, 5, 6, 13, 25	2	Research & Innovation	Low	Short-term=5 y
16. Land Degradation models' limitations, uncertainties and capabilities	Despite the existence of several models and methodologies to assess the Land Degradation status or components, there is a limitation in understanding their capabilities and uncertainties due to the lack of validation data and long-term measurements (Hessel et al. 2014, Saljnikov et al. 2022, European Commission 2020a, Aouragh et al. 2023, Li et al. 2021, Prăvălie et al. 2021, Xu et al. 2023).	Knowledge Development Gap					X	1, 2, 3, 5, 9, 11, 16	1, 6, 11, 12, 14	Research & Innovation	Low	Midterm= 10y
17. Lack of sufficient understanding of urban soils in relation to Land Degradation	As indicated in the Soil Mission Implementation Plan (European Commission 2019a), the scope of land/soil degradation knowledge predominantly revolves around agricultural soils, with limited attention given to other land uses. It is necessary to bridge this gap and enhance our capabilities for supporting and rejuvenating land and soil health, both in urban and rural areas.	Knowledge Development Gap			X			1, 2, 3, 5, 9, 11, 16	1, 2, 6, 11, 12, 15	Research & Innovation	Low	Midterm= 10y
18. Difficulties in understanding the drivers of individual and collective decisions associated with Land Degradation	Understanding the drivers behind individual and collective decisions is crucial for addressing land degradation effectively. Individual or collective decisions made by land users, such as farmers or landowners, play a significant role in shaping land management practices (Boardman and Evans 2019, European Commission 2019a, EU Soil Observatory 2019). Despite advancements in research, there are still difficulties in understanding individuals' decisions as decision-making is dynamic (it evolves over time in response to changing conditions), is represented by an inherent diversity (decision-making heterogeneity) and there is lack of data to capture the behavioural factors (EJP Soil 2018).	Knowledge Development Gap					X	1, 2, 3, 5, 7, 9, 10, 11, 16, 21, 27	1, 2, 6, 9, 11, 12, 13, 14	Research & Innovation	Low	Short-term=5 y

DOI: 10.5281/zenodo.17430539

			Sector						Actions			
Knowledge gap	Short description	Type of KG	Agriculture	Forest	Urban and industrial	Nature	Multiple	Bottlenecks	Action	Type of action	Priority	Timeframe
19. Lack of understanding of subsurface processes	The insufficient comprehension of subsurface processes associated with land/soil degradation underscores a notable gap in current research and data acquisition efforts. In comparison to topsoil, subsurface processes have not received a proportionate level of scrutiny. This incompatibility is further exacerbated by the fact that a predominant portion of existing Land Degradation and soil datasets (e.g. Soil Organic Carbon), as well as research projects and initiatives, predominantly concentrates on the topsoil layer (European Commission 2019a).	Knowledge Development Gap					X	1, 2, 3, 5, 9, 11, 16, 23		Research & Innovation	Low	Midterm= 10y
20. How to ensure land restoration is an integral part of social structures and actions at all scales?	Ensuring land restoration is integrated into social structures requires engaging local communities and utilizing their traditional knowledge and innovations, as emphasized by the Aichi Biodiversity target 8 (CBD 2014) (Economics of Land Degradation 2016). While local participation can significantly address land degradation, challenges arise from the limited technical capacity of these communities in natural resource management (Economics of Land Degradation 2016). Additionally, integrating land restoration into social structures, particularly in relation to indigenous knowledge, can be difficult (Santini and Miquelajauregui 2022). Although some studies show the potential of indigenous knowledge in enhancing land restoration, consistent success and benefits for communities remain elusive (Tellez et al. 2019). Further research is needed to explore social dynamics and identify factors that lead to successful restoration efforts that also benefit local rural communities (Wehi and Lord 2017, Reyes-García et al. 2018, Van Noordwijk et al. 2020).	Knowledge Development Gap					X	1-13, 15, 16, 17, 20-27	All actions	Research & Innovation	Low	Midterm= 10y
21. How to build commons-based land governance systems?	Contemplating land-based commons allows us to delve into the intricate dynamics of how individuals, communities, and humanity navigate interconnected natural and social environments (Giraud et al. 2016). From there, we can assess which organizational levels hold the greatest significance in understanding the interaction among customary, informal, and formal rules and practices. By incorporating these insights, we can craft adaptive approaches to natural resources management and delve into how territorial development strategies and organizational structures might impact the future of highly coveted land, such as arable and irrigable areas, as well as vulnerable territories like grazing and wildlife zones, forests, mountain tops, sacred sites, lakes and rivers - areas often targeted for land grabbing (International Land Coalition 2016). However, there are still existing challenges in establishing transparent and effective land governance systems (Giraud et al. 2016).	Knowledge Development & Application Gap					X	5, 6, 7, 15, 24	1, 2, 4, 5, 9	Research & Innovation	Low	Midterm= 10y

DOI: 10.5281/zenodo.17430539

			Sector					Actions				
Knowledge gap	Short description	Type of KG	Agriculture	Forest	Urban and industrial	Nature	Multiple	Bottlenecks	Action	Type of action	Priority	Timeframe
22. How do we shift from the current trend of intensification of agricultural production and overexploitation to land conservation?	More precisely, during the last decades, the EU's rapidly expanding population has placed increasing demands on essential resources like food and fiber, necessitating a substantial boost in agricultural production. Modern agricultural technologies, such as machinery, fertilizers, and advanced irrigation, are crucial to meet this demand. However, large-scale construction and environmetal challenges like climate change also stress European resources, particularly agricultural land (F.A.O. 2015). Soil, a non-renewable resource formed over millennia, is central to food, energy, and water security, as it supports over 95% of global food production (Saljnikov et al. 2022). Yet, the pursuit of higher agricultural output through technology can accelerate soil degradation to a critical point where further advancements can't compensate for soil limitations (Saljnikov et al. 2022).	Knowledge Development Gap	X	X				4, 5, 6, 7, 10, 15, 17, 27	1, 2, 4, 5, 7, 9, 13	Research & Innovation	Low	Midterm= 10y
23. How can we support land workers-led research on Land Degradation and how can we integrate the outputs of such endeavors?	Citizen science is an untapped resource for European soil and land research. In this light, the recent years the EU has been investing in a cornucopia of actions and projects to engage citizens in soil science and support them to preserve soil health (Panagos et al. 2024). Such actions and projects refer to but are not limited to the Soil funDamentals project, the UKSO Soil Observatory, the Grow observatoy, the ECHO project, the Soil Plastics monitoring application, and the Heavy Metal City Zen project. Despite the significance and the achievements of these efforts, there is a need to better communicate soil science to the plausible citizen scientists and a need to integrate the outputs of these projects (Wadoux and McBratney 2023).	Knowledge Development Gap					X	1, 2, 3, 5, 9, 11, 16	1, 2, 4, 7, 13	Research & Innovation	Low	Short-term=5 y
24. How can we overcome the challenges in the land regulatory framework introduced by land ownership?	As land is not a common good.	Knowledge Application Gap					X	6	2, 5	Research & Innovation	Low	Long-term>10y
25. Lack of understanding Nature Based Solutions	Not well studied yet (Dunlop et al. 2024).	Knowledge Development Gap	X	X		X	X	1, 2, 3, 5, 6, 9, 11, 15, 16	1, 2, 7, 13	Research & Innovation	Low	Short-term=5 y
26. Is it possible to identify sets of adaptation options that complement each other, mitigating trade-offs and fostering mutually beneficial outcomes for both climate change and land degradation?	(Reed and Stringer 2016)	Knowledge Application Gap	X	X	X	X	X	1, 2, 3, 5, 8, 9, 11, 13, 15, 16, 18, 19, 20, 25	1, 2, 3, 7, 10, 11, 12, 14, 15	Research & Innovation	Low	Long-term>10y
27. At what spatial scale do Land Degradation vulnerability maps offer the most valuable insights to decision-makers while maintaining a rich level of information and detail?	(Reed and Stringer 2016)	Knowledge Development Gap	X	X	X	X	X	1, 2, 3, 5, 8, 9, 11, 13, 16, 26	1, 2, 3, 7, 10, 11, 12, 14, 16	Research & Innovation	Low	Short-term=5 y

DOI: 10.5281/zenodo.17430539

			Sector						Actions			
Knowledge gap	Short description	Type of KG	Agriculture	Forest	Urban and industrial	Nature	Multiple	Bottlenecks	Action	Type of action	Priority	Timeframe
28. What resources are required for studying Land Degradation, and how do the monitoring (action) costs compare with the costs of not monitoring (inaction) across short, medium, and long-time frames?	(Reed and Stringer 2016)	Knowledge Development Gap	X	X	X	X	X	5, 15	1, 2	Research & Innovation	Low	Long-term>10y
29. How do we pinpoint the thresholds, both in terms of time and space, at which Land Degradation adaptive practices and technologies may turn counterproductive, warranting discouragement of their widespread adoption	(Reed and Stringer 2016)	Knowledge Development Gap	X	X	X	X	X	1, 2, 3, 5, 8, 9, 11, 13, 16, 20, 22	1, 2, 6, 11, 12, 14, 15	Research & Innovation	Low	Midterm= 10y
30. What is the optimal resolution and frequency of monitoring to provide decision-makers with crucial information on key variables associated with climate change and land degradation?	(Reed and Stringer 2016)	Knowledge Development Gap	X	X	X	X	X	1, 2, 3, 5, 8, 9, 11, 13, 16, 26	1, 2, 7, 10, 11, 12, 14	Research & Innovation	Low	Midterm= 10y
31. How can we harmonize findings from monitoring both slow and fast Land Degradation -related variables?	(Reed and Stringer 2016)	Knowledge Development Gap	X	X	X	X	X	3	1, 2	Research & Innovation	Low	Midterm= 10y
32. How can we sufficiently control water resources to avoid provoking issues in soils? How could the water directive be adjusted?	Water and land degradation are deeply interconnected, with one often intensifying the other (Borrelli et al. 2020). Water contributes to land degradation through erosion, which removes fertile soil (García-Ruiz et al. 2015), salinization from excessive irrigation (Mohanavelu et al. 2021), waterlogging due to poor drainage (Ritzema et al. 2008), and flooding that erodes land and deposits sediments (IPCC 2021). Conversely, land degradation reduces water availability (Lal 2015), increases runoff and flood risks (Montanarella et al. 2016), and contaminates water sources with sediments and pollutants (United Nations Convention to Combat Desertification 2022). However, current policies fail to integrate soil and water management, overlooking critical feedback loops such as salinization from poor irrigation practices, emphasizing the need for cohesive governance strategies.	Knowledge Development & Application Gap	X	X	X	X	X	1, 2, 3, 5, 6, 9, 11, 16	1, 2, 5	Research & Innovation	Low	Short-term=5 y

DOI: 10.5281/zenodo.17430539

Knowledge gap	Short description	Type of KG	Sector: Agriculture	Sector: Forest	Sector: Urban and industrial	Sector: Nature	Sector: Multiple	Bottlenecks	Actions: Action	Actions: Type of action	Priority	Timeframe
ADDITIONAL KNOWLEDGE GAPS (not based on literature) FROM STAKEHOLDERS INSIGHTS DURING THE CONSORTIUM MEETINGS, WORKSHOPS AND DISSEMINATION ACTIVITIES												
33. Administering arable agriculture and agroforestry systems with a focus on organic carbon poses a challenge.					As the decline in organic carbon is linked to the difficulty of implementing existing knowledge into practice/practical policies							
34. There is insufficient awareness and recognition of the risk of arable land loss.					How can we effectively convey knowledge about this risk?							
35. What are the green investments for Land Degradation?					Green investments for Land Degradation will facilitate EU actions concerning climate change and will result in much quicker reactions. However, there are gaps in terms of resource allocation (how can government budget and private sector investments tackle Land Degradation?) and the strengthening of political will to face the issue.							
36. How can farmers manage their animals more effectively regarding Land Degradation?												
37. How can we alter the thinking-behaviour of farmers, consumers, markets and society towards Land Degradation Neutrality?												
38. What are the solutions, awarding-motivation schemes, and policies to revive farmers' hope?												
39. What are the means to further educate policy makers so they can support better practices towards sustainability and Land Degradation Neutrality?												
40. How can we tackle the existing issues in policy implementation and how can we better align all the Land Degradation related policies with each other?												
41. How can we enhance knowledge transfer?												
42. How do we deal with the markets?					There is a need to create a balance between Land Degradation and markets/ecological economics (European Commission 2020a).							
43. What is considered a sustainable treatment for land and soil?					How soil health is defined?							
44. What are the risks associated with Land Degradation and ice caps?					What will happen and why?							

DOI: 10.5281/zenodo.17430539

Supplementary material 2

Table 3 Activities

Author: Melpomeni Zoka

Data type: Table

Activities									
LD Roadmap									
No	action title	"action short description (technical and socio-economic options that benefit the implementation of the TT relevant Soil Mission objectives)"	action type		time frame			"stakeholders involved (stakeholder groups or specific stakeholders)"	link to further actions (No)
			innovation	research	short	middle	long		
1	More focused research concerning LD	More research is needed to fill these knowledge gaps and develop a better understanding of the complexities involved and interlinkages between various drivers, processes and impacts concerning LD.		x	x	x		Academia	the majority of the actions
2	LD Roadmamps generation	Generate LD roadmaps that will facilitate the decision-making processes by providing tools that will outline the direction that should be taken to achieve the inclusion and prioritization of LD in the Soil Law and meet the long-term goals of the project regarding a Land Degradation Neutral EU.	x	x	x			Academia, Industry, Government, Society	all
3	Development and Implementation of physical solutions towards LDN	Existing measures largely focus on raising awareness, institutional development, or policy formulation. However, the actual execution of physical solutions to mitigate LD, lags behind.	x	x	x	x		Academia, Industry, Government, Society	1, 4, 5, 6, 7, 9, 10, 12, 14
4	Influence behavioral change associated with LD		x		x	x		Government, Academia	1, 2, 5, 7, 9, 13
5	Formulate effective policy actions concerning LD		x		x	x		Government, Academia	1, 2, 10
6	Provide adequate datasets that can be utilized in LD related research		x	x	x	x		Government, Academia, Industry	5, 10, 11, 12, 14
7	Increase LD-related training for farmers, advisors and land/soil related actors		x		x	x		Government, Academia, Industry, Society	1, 2, 3, 9, 13
8	The EU released the Sustainable Carbon Cycles (Carbon Farming) Policy Communication in December 2021, to be followed by a regulatory framework for an EU certification of carbon removals later that year.	The goal is for carbon farming initiatives to contribute 42 Megatons of CO2 equivalent (Mt CO2e) storage per year to Europe's natural carbon sinks by 2030, which represents approximately 20% of today's natural carbon sink	x		x	x	x	Government, Academia, Industry, Society	1, 2, 9, 10, 11, 12, 14
9	Agricultural rewarding	A system that rewards land degradation prevention, ecosystem services, biomass production, carbon sequestration, and biodiversity alongside traditional agricultural outputs.	x	x	x	x	x	Government, Academia, Industry, Society	1, 2, 3, 4, 7, 8, 10

DOI: 10.5281/zenodo.17430539

Activities									
LD Roadmap									
No	action title	"action short description (technical and socio-economic options that benefit the implementation of the TT relevant Soil Mission objectives)"	action type		time frame			"stakeholders involved (stakeholder groups or specific stakeholders)"	link to further actions (No)
			innovation	research	short	middle	long		
10	Set very clear guidelines on how to establish methodologies for project-level baseline emissions measurement and MRV (Monitoring, Reporting and Verification) for land and soils	At the moment, there is large variation in how individual projects establish a baseline and estimate changes in land/soil quality indicators over time. Clarity would enable large-scale, results-based rewards to farmers and provide incentives for continuous improvement instead of "just" compliance with guidelines. The baseline and MRV guidelines for voluntary projects should align with monitoring and compliance systems used in national GHG inventories and agricultural and land use statistics. The project data can then be used to enhance EU or national data systems, thereby increasing their robustness and cost-effectiveness.	x	x	x	x		Government, Academia	1, 2, 3, 5, 6, 8, 9, 11, 12, 14
11	Make LD pilots more precise with more data points on soil quality	Estimating e.g. soil organic carbon (SOC) content and SOC stock changes due to management practices requires lots of granular data on soil properties over a medium- to long-term time horizon. There are significant focus and resources at the EU level to improve EU and national soil monitoring data and compliance systems for EU regulations.		x	x	x		Government, Academia	5, 6, 10, 12, 14
12	EU Soil Quality database	A soil quality database will have multiple benefits for soil health enhancement in relation to climate change, biodiversity loss, socio-economic pathways and ecosystem services. For example, under the revised Land Use, Land Use Change and Forestry (LULUCF) Regulation proposal, Member States need to improve their data related to soil carbon and non-CO2 gases as well. The Carbon Farming Communication says that every land manager should have access to verified GHG emissions and removal data by 2028 and that carbon farming initiatives should contribute to the new net carbon removal target of 310 Mt CO2e by 2030. These initiatives are also key to reaching the 2035 AFOLU net-zero target. Currently, the JRCs Soil related Working Groups are gathering, analysing and storing soil data throughout the European region	x	x	x	x		Academia, Industry, Government, Society	5, 6, 10, 11, 14
13	Interactions with land users beyond farming	Much of the LD has to do with the lack of regional planning for industry and services location. Also, in the case of unhealthy soils there's the tendency of not acting to reverse the situation and take care of soils. Society/citizens still are passive in relation to public environmental goods, like the land.	x		x	x		Academia, Industry, Government, Society	1, 2, 3, 4, 7
14	A novel soil health dashboard within the EU Soil Observatory	A novel soil health dashboard within the EU Soil Observatory highlights the location and estimates the extent of unhealthy soils in the EU, as well as the degradation processes behind them. This proposal is part of the EU soil strategy for 2030. Its aim is to specify the conditions for a healthy soil, determine options for monitoring soil, and lay out rules conducive to sustainable soil use and restoration. https://joint-research-centre.ec.europa.eu/jrc-news-and-updates/new-tool-maps-state-soil-health-across-europe-2023-03-13_en	x	x	x			Academia, Industry, Government, Society	5, 6, 10, 11, 12
15	Reversal modelling for LD	Plan for future prevention and restoration of Land	x	x	x	x		Academia, Business, NGOS, Government, Society	

DOI: 10.5281/zenodo.17430539

Supplementary material 3

Table 4 Bottlenecks

Author: Melpomeni Zoka

Data type: Table

Major bottlenecks and risks hindering the impact of the Mission research and innovation activities in relation to Land Degradation (LD)												
LD Roadmap												
No	bottleneck title	bottleneck short description	bottleneck type					time frame			Link to further bottlenecks (No)
			social factors	environmental and ecological factors	economic factors and markets	legal aspects and legislative	governance and institutional arrangements	short	middle	long	
1	Lack of LD validation data	Ensuring the reliability and accuracy of LD-related research findings is a critical aspect of data validation, as it directly impacts the scientific foundation of projects. Unvalidated data can lead to misleading or erroneous results, potentially resulting in the adoption of ineffective strategies to combat LD. It hampers method optimization, limits the reproducibility of research outcomes, and can affect the allocation of resources and stakeholder confidence.	x	x	x	x	x	x			2, 3, 5, 8, 9, 11, 16, 20
2	Limited LD integrated monitoring and assessment system	There is a lack of standardized and widespread monitoring and assessment systems for LD. This makes it difficult to quantify and understand the extent and severity of LD in European level but also worldwide.	x	x	x		x	x	x		1, 3, 5, 8, 9, 11, 16
3	Absence of harmonized LD methodologies and data	This results in inconsistent comparisons across studies and regions, making it difficult to identify common trends and patterns in land degradation, leading to conflicting results and reduced scientific consensus and limiting the generalizability of research findings, hindering the development of evidence-based policies and effective resource allocation.	x	x	x	x	x	x	x		1, 2, 5, 8, 9, 11, 16
4	LD knowledge transfer, guidance and implementation/ utilisation	Bridging the gap between LD research and implementation is crucial to ensure that scientific knowledge is effectively communicated, rapidly absorbed and utilized by farmers, landowners, policymakers and the scientific community leading the way towards further innovation.	x		x		x	x			5, 6, 7, 8, 10, 12, 15, 17, 21, 27
5	Limited financial support and investement for LD	More financial support is needed to encourage and strengthen research and innovation in land degradation, which is fundamental for sustainable land management and food security.					x	x	x		all
6	Absence of well-established LD-related policies and legislations	Lack of LD-related policies frameworks, obligatory targets and timelines lead to unclear guidelines for land and soil management, resulting in a lack of standardization in LD R&I methodologies. It also translates into insufficient funding, restricting the scope and effectiveness of LD research. Moreover, the absence of policies hampers coordination among stakeholders and diminishes incentives for engagement in LD R&I activities.	x		x	x	x	x	x		5, 7, 8, 14, 15, 17, 18, 24, 25, 26
7	Incompliance with policies	The scientific and non-scientific community sometimes fail to adhere to established policies for land/soil management and conservation. That is because these policies are not very strict or there are no incentives for researchers and general public to engage in LD management. As a result, unregulated and unsustainable land-use practices might be used, exacerbating land degradation. This non-compliance can also lead to resource misallocation, as funds meant for sustainable soil management may be diverted to address for example the consequences of non-compliance, limiting the impact of R&I projects.	x			x	x	x	x		5, 6, 8, 14, 15, 17, 18, 24, 25, 27

DOI: 10.5281/zenodo.17430539

Major bottlenecks and risks hindering the impact of the Mission research and innovation activities in relation to Land Degradation (LD)

LD Roadmap

No	bottleneck title	bottleneck short description	bottleneck type					time frame			Link to further bottlenecks (No)
			social factors	environmental and ecological factors	economic factors and markets	legal aspects and legislative	governance and institutional arrangements	short	middle	long	
8	Lack of EU inventory of LD	There is currently no comprehensive and systematic EU inventory of Land Degradation. Such an inventory could advocate for regionally tailored, sustainable land management strategies, which should be implemented and rigorously monitored.			x	x	x	x	x		1, 2, 3, 5, 7, 9, 11, 16
9	LD Digital Transformation	As stated in the EU Green Deal, Soil Mission Implementation Plan etc			x			x	x		all
10	LD awareness, education and engagement	Land and soil are often underestimated, seen merely as 'dirt,' and their critical role in sustainability and the circular bioeconomy is frequently overlooked due to limited public awareness and education. This lack of recognition hampers investments and political action to protect and enhance land and soil quality. It is of vital importance to raise awareness and engagement at a societal, political and financial level.	x		x		x	x	x	x	4, 5, 7, 12, 17, 20, 21, 26, 27
11	Long-term LD time series				x			x	x		1, 2, 3, 5, 7, 8, 9, 16
12	A lack of attractiveness of the LD-related incentives		x		x	x	x	x	x		4, 5, 7, 10, 15, 17, 18, 21, 27
13	A lack of tracking the long term progress of projects related to LD and soil health				x	x	x		x	x	5, 9
14	A lack of clear LD definitions hinder the targets effectiveness					x	x	x	x		6, 7, 21
15	A lack of a LD cost-benefit analysis regarding the utilization of land/soil sustainable management practices (Return of Investment)		x		x	x		x	x		5, 6, 7, 8, 9, 10, 17, 18, 26
16	LD data fragmentation	Lack of common data policy, dispersed storage of data, often not available to the public, lack of validation and integration of large data sets				x	x	x	x	x	1, 2, 3, 5, 8, 9, 11
17	Lack of valorization of land and soil care, awarding the users that clearly care about soil	Need to increase the economic and social support for soil care	x		x	x	x	x	x	x	4, 5, 7, 8, 9, 10, 12, 15, 18, 21, 26, 27
18	Challenges in EU Carbon removal certification scheme	Persistent challenges remain around monitoring, reporting, and verification (MRV); non-transparency and uncertainty around carbon credit prices; and the unattractive cost-benefit of changing farming practices.	x	x	x	x	x	x	x		the majority of the bottlenecks

DOI: 10.5281/zenodo.17430539

Major bottlenecks and risks hindering the impact of the Mission research and innovation activities in relation to Land Degradation (LD)											
LD Roadmap											
No	bottleneck title	bottleneck short description	bottleneck type					time frame			Link to further bottlenecks (No)
			social factors	environmental and ecological factors	economic factors and markets	legal aspects and legislative	governance and institutional arrangements	short	middle	long	
19	Risks of permanence and reversal in land-based carbon removal	Changing agricultural land management practices offers significant climate mitigation potential. However, agriculture and carbon sequestration are vulnerable to weather and climate-related events. The permanence of soil carbon is not guaranteed in agriculture. It could be disrupted, for example, by future management decisions (e.g. by a successor or new land owner-renter) or natural disasters. Yet, this non-permanence is inconsistently addressed across protocols. The new carbon removal guidance needs to have robust mechanisms that address non-permanence and reversal risks in a conservative manner. Such mechanisms could include conservative buffer pools, 100 years of required permanence, or ton-year accounting recommendations.		x		x		x	x	x	4, 5, 6, 8, 9, 10, 12, 18, 25
20	Imbalance in the distribution of the financial resources across the EU countries		x		x		x	x			5
21	Language barriers		x		x			x			5, 7, 10, 12
22	The majority of the projects provide information, frameworks and guidelines per (bio) climatic zone and not for every EU Member State			x		x		x	x		5, 20
23	Limited depth of penetration	One of the primary challenges is the limited depth of penetration of the current remote sensing systems. More ppprecisely, traditional satellite remote sensing systems, except for radar systems with a penetration depth of solely a few cm, primarily capture surface-level information. This leaves a substantial portion of the subsurface unexplored, hindering a comprehensive understanding of land/soil dynamics at deeper levels.			x			x	x	x	5
24	Limited LD regulations	Lack of LD regulations to prevent damages, as well to restore (obligation and financial support).				x		x	x		5, 6, 7, 8, 14, 15, 17, 18, 25, 26
25	Difficulties to capture information regarding LD and climate change - biodiversity loss related investments	Climate change or biodiversity conservation investments can deliver co benefits for land quality but these are not assessed in such a way that allows this information to be captured			x	x	x	x	x		5, 6, 7, 8, 14, 15, 17, 18, 24, 26
26	Insufficient analysis	Lack of analysis of how tradeoffs (and co benefits) in relation to particular land management decision making evolves over time.			x	x	x	x	x		5, 6, 7, 8, 14, 15, 17, 18, 24, 25
27	Limited communication with and/or to practice	1/ communication to practice = very limited efficiency of new methods/techniques implementation to e.g., farmers (via scientists not speaking Chinese with farmers or via any mediator(s) who will get the skill to translate and negotiate with them); 2/ communication with practice = vice-versa "listening of e.g., those farmers What is needed! and consequent formulation of the scientific questions/hypotheses based of that simple question "What is needed...?"	x		x	x	x	x	x		4, 5, 7, 10, 12, 17, 20, 21, 26

DOI: 10.5281/zenodo.17430539

Supplementary material 4

Table 1 Top 10 Knowledge Gaps

Author: Melpomeni Zoka
Data type: Table

Rank	Knowledge gap	Type of knowledge gap
1	What are the most efficient and cost-effective Land Degradation prevention and restoration measures incorporating an assessment of trade-offs between different land uses and pedo-climatic zones?	Knowledge Development Gap
2	Lack of thorough understanding of the interactions between Land Degradation and Ecosystem Services?	Knowledge Development Gap
3	Historical, current and future social and economical interactions with Land Degradation.	Knowledge Development Gap
4	Lack of comprehensive understanding of Land Degradation (effects, drivers).	Knowledge Development Gap
5	How can we enhance regional planning regarding reducing Land Degradation?	Knowledge Application Gap
6	Lack of Land Degradation related data and limited monitoring at different scales	Knowledge Development Gap
7	How do we support the farmers to make the turning point towards sustainable land and soil management soil practices?	Knowledge Development Gap
8	Limited mitigation Land Degradation strategies	Knowledge Application Gap
9	How do we educate and inform the population more effectively about the value of natural resources, including soil.	Knowledge Application Gap
10	Is the concept of Land Degradation Neutrality enough to ensure healthy land and soils in the future?	Knowledge Development Gap

DOI: 10.5281/zenodo.17430539

Supplementary materials for “Outlook on the knowledge gaps to conserve and increase soil organic carbon stocks”

Supplementary material 1

Prioritized knowledge gaps, their sector impact, bottlenecks and suggested actions

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Data type: Qualitative

				Sector									
N.o	Knowledge gap	Short description	Type of knowledge gap	Agriculture	Forest	Urban/ industrial	Nature	Multiple	Bottlenecks	Action	Type of action	Priority	Timeframe
Key Knowledge Gaps													
1	Climate change adaptation	Climate change adaptationis a broad and interdisciplinary field of research, involving various disciplines, methods, and perspectives concerning soil health, quantification of SOC stocks, regional variability, mitigation strategies and integration with agricultural policies.. This knowledge gap identifies several topics requiring knowledge development for further research and innovation actions. Moreover, climate smart adaptation requires knowledge application research and innovation actions.	KDG	Likely to affect agricultural land use change; Management quality; and land use intensity	Tree species composition, rotation periods, and modifying stand structures		Species composition in marginal ecosystems may change		Development BN:(iin understanding the interaction between soil carbon and climate change adaptation lies in the complexity and unclear mechanisms of soil organic carbon (SOC) dynamics, particularly in relation to biogeochemical processes, biodiversity and the integration of empirical and modelling approachesApplication BN(ii) transferring existing soil research findings to practitioners, hindering the adoption of sustainable soil managementpractices	(i) More experimental research is needed to study the long-term dynamics of trade-offs and synergies in SOC sequestration under varioussoil management strategies; (ii) there is also need to developing models and monitoring programs to better understand soil carbon stocks and degradation iscrucial; (iii) research should provide further knowledge on how soil structure, management practises and extreme weather events impact organic carbon stocks, and how this interacts with functional biodiversity. It’s also (iv) essential to provide regional-specific long-term knowledge for tailoring adaptation strategies; (v) final, there is also a need to increase the understanding on the indirect effects of adaptation practices on soil functions and biodiversity.	Research and Innovation action	High	According to: Short-term = 5 y Midterm = 10y Long-term > 10y
			KAG							(i) Research should focus on practices that promote SOC accumulation while balancing trade-offs between climate adaptation, food security, and ecosystem services;.(ii) transfer existing research to practical applications remainsinsufficient (iii) assess these effects, research on harmonising measuring, accounting, monitoring and model development across Europe is required			

DOI: 10.5281/zenodo.17430539

N.o	Knowledge gap	Short description	Type of knowledge gap	Sector: Agriculture	Sector: Forest	Sector: Urban/ industrial	Sector: Nature	Sector: Multiple	Bottlenecks	Action	Type of action	Priority	Timeframe
2	Biodiversity interaction between soil carbon and biology	Soil biodiversity plays critical roles in delivering ecosystem goods and services, such as nutrient cycling, water regulation, and soil structure maintenance. Biodiverse ecosystems may enhance SOC storage capacity and research can identify which plant species or microbial communities promote SOC accumulation.	KDG	Likely to affect agricultural land use change; Management quality; and land use intensity					Development BN:(i) evidence of congruence between biodiversity and carbon stocks, the mechanisms driving these relationships are not well understood. (ii) There is a need to understand how belowground communities, including microbes and invertebrates, influence SOC turnover and ecosystemfunctioning. (iii) The effects of biodiversity on SOC in are poorly understood, particularly under conditions of ecological novelty such as high numbers of non-native species and urbandisturbances. (iv) The balance between increased litter inputs and microbial respiration needs further exploration to understand how plant diversity affects SOC across differentecosystem and (v) There is uncertainty about how different measures of biodiversity, such as species diversity and functional traits, affect carbon stocks in forest ecosystems. Application BN(i) how current policies can adequately address the complex interactions between biodiversity and SOC. (ii) understanding the role of soil microorganisms and biodiversity in stabilizing soil organicmatter agricultural and forest management practices to enhance SOC storage.	(i) Integrate belowground biological processes into SOC models to improve carbon managementstrategies. (ii) Developing high-resolution maps and models to predict soil biodiversity and SOC is crucial. This includes using digital soil mapping and regression analysis to link soil attributes withbiodiversity.	Research and Innovation action	High	According to: Short-term = 5 y Midterm = 10y Long-term > 10y
			KAG							(i) An integrative approach that includes setting baselines, monitoring threats, and establishing soil indicators isrecommended, and (ii) encouraging sustainable land-use practices and reducing agricultural intensification can help preserve soil biodiversity. Providing incentives for sustainable practices and improving knowledge access are alsosuggested.			
3	Policy and decision support	Policy making and decision support requires knowledge exchange and implementation of already existing information, thus concentrating on the deficient links between available knowledge and its implementation and application.	KAG	Likely to affect agricultural land use change; Management quality; and land use intensity					Application BN:(i). There are doubts and uncertainties related to the how soils can or should be used to sequester carbon to mitigate or adapt to climate change. (ii). The policy support and the implementation of techniques that could improve carbon sequestration is a highly sensitive and more research is required to understand the long term consequences.	(i) Strengthen the role of knowledge brokers and improve the relevance of research activities for land users through targeted advice and informationdissemination; (ii) Encourage research that integrates social and ecological systems to develop comprehensive soil carbon managementstrategies; (iii) Promote studies in underrepresented regions to ensure a more global understanding of SOCdynamics, and to (iv) Invest in monitoring and modelling frameworks to provide robust data for decision-making and policydevelopment.	Research and Innovation action	High	According to: Short-term = 5 y Midterm = 10y Long-term > 10y

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				Sector									
N.o	Knowledge gap	Short description	Type of knowledge gap	Agriculture	Forest	Urban/ industrial	Nature	Multiple	Bottlenecks	Action	Type of action	Priority	Timeframe
Prioritisation of knowledge gaps													
1	Soil carbon measuring, accounting and monitoring	Several studies collectively point to the need for standardized, cost-efficient, and reliable methods that can be applied at various scales, and the potential of data-driven approaches and global frameworks to address these gaps	KDG						Development BN(i) understanding the distribution and dynamics of soil carbon stocks across different land uses and regions in Europe is incomplete.(i) a lack of long-term datasets and standardized samplingprocedures(iii) The impact of environmental factors such as climate, soil pH, and land cover on SOC storage is not fully understoodApplication BN:(iii) The transfer of existing research findings to practical applications is insufficient, hindering the adoption of sustainable soil managementpractices	Development(i) Incorporating biological and physical parameters into existing monitoring frameworks for survey iscrucial and (ii) Developing standardized methods for data collection and analysis, along with improved data sharing across countries, is essential for accurate SOC estimation and policysupport	Research and Innovation action	High	According to: Short-term = 5 y Midterm = 10y Long-term > 10y
			KAG							Application:Raising awareness and improving communication between researchers and practitioners can facilitate better implementation of soil managementstrategies.			
2	Circular bioeconomy	There is significant lack of knowledge concerning safe and energy-efficient recycling of waste materials in soil, and its impact on soil organic carbon stocks and soil health. We cannot make use of organic waste transferring contaminants, pathogenic organisms, and unwanted plant residues such as weed in healthy soils.	Both KDG & KAP						Development BN(i) There is a lack of precise methods to assess the impact of organic waste on soil health(ii) There is risk associated with recycling of organic waste in soils as such waste can introduce pollutants into soils. Application BN(iii) There is a disconnect between research findings and practical implementation in organic arable farming.(iv) Current legislation may not adequately protect soil ecosystems from the potential toxicity of organic wastes.	Development:(i) Enhance research on microbial interactions and nutrient cycling in soils with organic amendments to improve carbon sequestration models and nutrient managementstrategies (ii)Conduct more detailed studies on the effects of organic waste on various soil organisms to better understand and mitigate potential toxicimpacts (iii) Develop more precise and comprehensive methods for monitoring soil structure changes and pollutant levels, including advanced imaging and chemical analysistechniquesApplication:(i) Implement better waste management practices that consider the complex interactions of different waste types and their potential environmentalimpacts (ii) Increase data collection on soil physical properties and promote sharing of findings to build a more comprehensive understanding of the effects of organic wasteapplications (iii) Revising policies to account for the complex interactions of organic waste components and their long-term effects on soil health and ecosystem stability iscrucial.	Research and Innovation action	High	According to: Short-term = 5 y Midterm = 10y Long-term > 10y

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				Sector									
N.o	Knowledge gap	Short description	Type of knowledge gap	Agriculture	Forest	Urban/ industrial	Nature	Multiple	Bottlenecks	Action	Type of action	Priority	Timeframe
3	Agronomic system approach	There are several knowledge gaps on various aspects of agronomic practices for managing soil organic carbon stocks in agricultural soils, and long-term field experiments trying to elucidate the effect of different soil management practices on soil carbon stocks need long-term perspectives (and appropriate financing possibilities)	Both KDG and KAG						Development BN:(i) understanding the trade-offs and synergies of soil management strategies (SMS) on SOC sequestration, greenhouse gas emissions, and nutrientleaching.(ii), there is a lack of comprehensive data on soil carbon stocks, soil degradation, and fertility, which hinders the development of improved soil managementstrategiesApplication BN:(iii)The impact of agronomic systems on soil organic carbon (SOC) in Europe is limited mostly due to insufficient communication and lack of standardized methodologies	Development:(i) More experimental research is needed to study the impact of pedoclimatic conditions and long-term dynamics of SMS on SOC andemissions; (ii) Developing models and monitoring programs to better understand soil processes iscrucial Application:(i)Increase awareness among stakeholders about the importance of SOC and sustainable soil managementpractices (ii) Enhance the role of intermediaries who can effectively communicate research findings to practitioners andpolicymakers (iii) Align research activities with the needs of land users and ensure that findings are accessible andapplicable (iV) Introduce financial incentives, such as subsidies and payments for ecosystem services, to encourage the adoption of sustainablepractices, and probably very important (v) encourage direct communication among farmers and stakeholders to share experiences and bestpractices.	Research and Innovation action	High	According to: Short-term = 5 y Midterm = 10y Long-term > 10y
4	Urbanization	Urbanization is the process of transforming rural areas into urban areas, which can have various effects on food production and soil organic carbon (SOC) stocks. Thus, integrating soil health and carbon sequestration goals into urban planning and policies will be challenging. Several unsolved questions remain	Both KDG and KAG	Likely to affect agricultural land use change; Management quality; and land use intensity					Development BN:(i) limited data on urban soil carbon storage and the variability in SOC stocks across different urban land uses and regions(ii) the effects of different urbanization pathways on SOC stocks are complex and not fully understood, particularly in contrasting climaticconditions. This hinders accurate SOC stock estimations and their inclusion in regional and national carbonbudgetsApplication BN:(iii) applying existing knowledge about the impact of urban sprawl on soil organic carbon (SOC) stocks in Europe is the inadequate integration and communication of research findings to practitioners and policymakers.	Development(i) Implement soil and land-use management practices that enhance SOC stocks and support ecosystem services in urbanareas (ii) Increase efforts to collect and analyse SOC data across various urban land uses and regions to improve accuracy in SOC stockestimations (iii) Encourage the development of urban green spaces, such as parks and gardens, which have been shown to retain higher SOC stocks compared to other urban landuses (iv) Adopt strategies to control urban sprawl and promote resource-efficient land use, which can help mitigate the negative impacts on SOCstocks	Research and Innovation action	High	According to: Short-term = 5 y Midterm = 10y Long-term > 10y

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				Sector									
N.o	Knowledge gap	Short description	Type of knowledge gap	Agriculture	Forest	Urban/ industrial	Nature	Multiple	Bottlenecks	Action	Type of action	Priority	Timeframe
5	Education and awareness raising	There is a great need for education that increases awareness and knowledge of the conservation of soil organic carbon stocks in sustaining life and natural resources from the individual to the societal level	Both KDG and KAG						Application BN:the importance of soil organic carbon (SOC), particularly in education and awareness, and application of existing research to practitioners and the public is not effectively communicated	(i) Enhancing the role of intermediaries who can translate scientific findings into practical advice for landusers, (ii) encouraging communication among farmers and stakeholders to share best practices andexperiences (iii) providing tailored advice and information that considers local environmental and socio-economicconditions, (iv) raising awareness about the importance of SOC and strengthening educational programs are essential. This includes providing credible information and locally relevant advice tostakeholders (v) funding for applied research, and support for training programs can encourage the adoption of sustainablepractice	Research and Innovation action	High	According to: Short-term = 5 y Midterm = 10y Long-term > 10y
6	Forest Management	Forest soils store almost half of the total organic carbon in terrestrial ecosystems, and forest management practices can influence the rates of input or release of carbon from soils. Research on forestry and practices require more long-term soil monitoring, experimental studies, and synthesis of existing data to provide evidence-based guidance for climate smart forest management practices	Both KDG and KAG	Likely to affect forest land use change; Management quality; and land use intensity					(i) understanding how different practices impact SOC stocks and interact with environmental factors like climate change	(i) Utilize large observational databases and meta-analyses can help synthesize existing data and provide a clearer picture of SOC dynamics across different regions and managementpractices, (ii) Creating comprehensive classifications and thesauri, like DATA4C+, can help standardize the description of management practices and improve the quality of meta-analyses, aiding in the identification of effective SOC managementstrategies, (iii) Research should prioritize understanding how climate change scenarios affect SOC, as these changes pose significant risks to SOC stocks, particularly in temperateforests.	Combination of modelling, knowledge transfer, research and Innovation action	High	According to: Short-term = 5 y Midterm = 10y Long-term > 10y
7	EU footprints of soil carbon outside Europe	Current knowledge gaps to improve our understanding on soil organic carbon (SOC) stock outside Europe highlight the need for standardized estimation on the effect of global land use change, European carbon footprints, how policy making affect SOC conservation, global biodiversity, the importance in having access to comprehensive data sets and accurate mapping techniques	Both KDG and KAG						(i) understanding European impacts on global SOC stocks is the lack of comprehensive monitoring of how European consumption and land use affect SOC worldwide. (ii) insufficient data on environmental factors influencing SOC storage and the effects of trade and consumption patterns outside Europe.	(i) Enhance the integration of research findings into policymaking to address the impacts of European consumption on global SOC stocks. This includes considering trade impacts in national and regionalpolicies (ii) Promote standardization in SOC measurement and data sharing across countries to improve the accuracy of SOC assessments and facilitate better policydecisions (iii) Implement incentives for sustainable soil management practices that enhance SOC sequestration, such as carbon credits and other financialmechanisms			

DOI: 10.5281/zenodo.17430539

Supplementary materials for “Outlook on the knowledge gaps to reduce soil sealing and increase the reuse of urban soil”

Supplementary material 1

Knowledge gaps, bottlenecks and actions

Author: All authors

Data type: Table

Knowledge gap	Short description	Type of KG	Sector					Bottlenecks	Actions			
			Agriculture	Forest	Urban and industrial	Nature	Multiple		Action	Type of action	Priority	Timeframe
New policy approaches and instruments to reduce soil sealing	*Need for innovative policy instruments to promote the no net soil sealing target.*	*Knowledge development gap*			*Urban and industrial*			• *Insufficient mandatory assessment of the environmental impacts of policies, including on soil and related functions and services (e.g., through SEA and EIA) hinders sustainable decision-making* • *Policymakers’ limited awareness creates a hinders informed decision-making*	*Mainstream sealing prevention and soil restoration in all policies, including different incentive schemes*	*Innovation*	*High*	*Short*
								• *Limited understanding of funding scheme trade-offs hinders informed resource allocation* • *The absence of systematic monitoring of policy impacts hinders effective evaluation and improvement*	*Analyse the effectiveness and trade-offs of funding schemes*	*Research*		*Middle*
								The complexity of ecosystem services modelling hinders the development of compensation schemes	*Develop simple decision frameworks for local policymakers to evaluate plans for reducing soil sealing and increasing ecosystem service provision*	*Innovation*		*Middle*
								Failure to adopt innovative political approaches to soil health across different scales hinders sustainable land management	*Develop effective framework programs and economic tools (e.g., taxes, incentives, eco-budgeting schemes) to prevent soil sealing and compensate its impacts*	*Innovation*		*Middle*
								• *The absence of simple and comprehensive tools for assessing soil ecosystem services as a whole (e.g., scoring systems) hinders the development of schemes to prevent land take and soil sealing.* • *The absence of systematic monitoring of policy impacts hinders effective evaluation and improvement*	*Develop and test fair compensation schemes for soil sealing based on the assessment of ecosystem functions and services*	*Innovation*		*Middle*
								Land regulatory ambiguities cause conflict between environmental protection goals and landowners’ property rights, particularly in a market-driven economy	*Develop schemes to prevent land take and soil sealing in various institutional settings, with particular attention to the role of landowners’ property rights*	*Research*		*Middle*

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Knowledge gap	Short description	Type of KG	Sector					Bottlenecks	Actions			
			Agriculture	Forest	Urban and industrial	Nature	Multiple		Action	Type of action	Priority	Timeframe
Best practices to promote the reuse of urban soils from construction sites	*Lack of a systematic collection and comparison of existing best practices of certifying soil quality and tracking soil transportation to facilitate the reuse of urban soils from construction sites.*	*Knowledge application gap*			*Urban and industrial*			*Unclear waste definitions hinder effective policies and guidance for reusing excavated urban soils*	*Develop widely-applicable methods to track soil transportation and the creation of new soils (constructed techno soils) from excavated soils and organic wastes*	*Innovation*	*High*	*Short*
								The absence of efficient methods for determining soil sustainability during construction causes delays and increasing costs	*Identify methods and approaches to reduce the risks of the reuse of materials from multiple perspectives (soil quality, financial, legal)*	*Research*		*Short*
								Inconsistent institutional capacity and resource distribution hinder the development of methods to increase knowledge exchange between more and less experienced Member States and organizations.	*Develop methods to increase knowledge exchange between more and less experienced Member States and organizations on remediation techniques, soil restoration and brownfield management*	*Research*		*Short*
								• *Diversity of national context and regulatory frameworks hinders harmonized policy implementation* • *Limited exchange of good practices and lessons learned across different contexts hinders the development of successful approaches and capacity building*	*Develop for all Member States guidance on how to draft a soil management strategy*	*Innovation*		*Short*
								Inconsistent monitoring approaches hinders the effective assessment of de-sealing actions/ measures on soils	*Promote research that monitors the effects of de-sealing interventions on soil*	*Research*		*Short*
Legal and regulatory dimension of soil sealing	*Lack of comparative analyses of the legal dimension of soil sealing and land take across EU Member States and of the opportunities to integrate the no net soil sealing objective in different contexts.*	*Knowledge development gap*			*Urban and industrial*			*The significant variation in soil sealing regulations and socio-economic contexts across European countries causes the necessity of having customized yet comparable approaches*	*Assess the legal and socio-economic dimension of soil sealing across Member States*	*Innovation*	*High*	*Short*
								The significant variation in soil sealing regulations and socio-economic contexts across European countries causes the necessity of having customized yet comparable approaches	*Assess the impact of property rights on soil sealing across EU countries*	*Innovation*		*Short*
								Limited availability and accessibility of data across different sources and institutions hinders effective analysis and decision-making	*Produce maps of publicly owned sealed land by combining data from various sources to identify areas where desealing interventions are more feasible, following the example of similar efforts in Flanders*	*Innovation*		*Short*
Effectiveness of desealing interventions	*Lack of knowledge about the effectiveness of desealing actions in restoring lost soil functions*	*Knowledge development gap*			*Urban and industrial*			*Lack of soil quality data*	*Promote soil quality monitoring*	*Innovation*	*High*	*Short*
								Lack of a suitable EU dataset to capture and track desealing activities	*Develop the use of soil data in national ecosystem assessment*	*Innovation*		*Middle*
								Need for standardized approaches for monitoring	*Promote research that monitors the effects of de-sealing interventions on soil*	*Research*		*Short*

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Knowledge gap	Short description	Type of KG	Sector					Bottlenecks	Actions			
			Agriculture	Forest	Urban and industrial	Nature	Multiple		Action	Type of action	Priority	Timeframe
Socio-economic impacts of no net soil sealing policies	*Lack of knowledge on suitable policy mixes to minimize the negative socio-economic impacts of no net soil sealing and no net land take policies (e g, unaffordable housing, rising inequalities).*	*Knowledge development gap*			*Urban and industrial*			*Lack of long-term data collection hinders the sustainability of measures*	*Establish and evaluate long-term records of prevention and restoration measures of soil (for different land use systems) with a focus on cost-effectiveness*	*Innovation*	*Moderate*	*Short*
								Lack of updated studies hinders the evaluation of no net soil sealing policies	*Evaluate no net soil sealing policies in the light of housing needs and population growth in different European countries*	*Research*		*Short*
								Conflict between conservation and development hinders coherent land use planning	*Assess of how property rights in EU countries restrict the implementation of no net soil sealing policies*	*Research*		*Middle*
								Complex coordination process makes decision-making and implementation difficult for test-sites	*Develop coordinated test-sites*	*Innovation*		*Short*
Minimum unsealed soil per person that ensure biodiversity and human health in urban areas	*Lack of unsealed soil thresholds and targets*	*Knowledge development gap*			*Urban and industrial*			*Lack of research linking unsealed soil with soil sealing levels*	*Develop and test indicators to assess soil characteristics for different soil types (also including industrial/ urban sites) and climate conditions and set up interpretation/ benchmark values (i.e thresholds, target values)*	*Research*	*Moderate*	*Short*
Drivers of soil sealing from individual to sectoral policies	*Lack of assessment of the impacts on soil sealing and land take of different decisions at the different sectoral policies (such as tourism, transport infrastructure and commerce) and the individual levels.*	*Knowledge development gap*			*Urban and industrial*			*Lack of interest makes it hard to mobilise actions or funding for soil sealing prevention*	*Identify sectors, agents, and relevant policies (in the EU) that affect soil health, soil sealing and land take inside and outside the EU*	*Innovation*	*Moderate*	*Short*
								Lack of sensitivity affects the urgency and inclusion of sealing in planning and policy discussions	*Develop protocols to assess intentional and unintentional effects of sectoral policies on soil sealing, taking stock of existing research*	*Research*		*Middle*
Typologies of soil sealing and their impact on soil functions and services	*Lack of a soil sealing classification based on soil properties, functions, and ecosystem services, considering both surface and underground processes of soil sealing.*	*Knowledge development gap*			*Urban and industrial*			*High variability of soil conditions hinders the establishment of universal reference values and targets for soil functions*	*Define references and target values of soil functions in the context of soil type and land use*	*Research*	*Moderate*	*Middle*
								There is a high variability of soil properties and soil functions across regions, land uses, and climatic conditions	*Deliver soil sealing database and maps of soil properties and soil functions*	*Innovation*		*Middle*

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Knowledge gap	Short description	Type of KG	Sector					Bottlenecks	Actions			
			Agriculture	Forest	Urban and industrial	Nature	Multiple		Action	Type of action	Priority	Timeframe
Acceptability and legitimacy of no net soil sealing policies	*Lack of understanding of the factors that affect the acceptability of no net soil sealing policies by different actors.*	*Knowledge development gap*			*Urban and industrial*			*Diverging stakeholder interests delay unified policy actions.*	*Identify the key stakeholders, their role, awareness and communication channels at different levels of no net soil sealing policies*	*Innovation*	*Moderate*	*Short*
								Scientific complexity limits understanding and slows policy development or communication	*Develop and test tailored education material to increase awareness about (i) benefits of functional / unsealed soils, GBI and NBS, (ii) preventing measures for different target groups and (iii) the potential of a nature-based economy for the local and regional economic development*	*Innovation*		*Short*
								Environmental education raises awareness, and a lack of it hinders behavioural and institutional change	*Assess the current state of soil education in school curricula at all levels and monitor changes*	*Innovation*		*Short*
								Missing soil content in curricula leads to future professional capacity gaps	*Co-develop soil literacy courses in relevant degrees (agronomy, environmental sciences, environmental engineering etc.) e.g for universities*	*Innovation*		*Short*
								Lack of a common interpretation of different definitions hinders the development of national soil monitoring programs	*Develop national soil monitoring programs will profit from an early involvement of stakeholders by promoting acceptance and shared interest in indicators, reference values and target values for soil quality, as well as from incorporation of practical knowledge on land management, service flow and the possibility to introduce payments for ecosystem services*	*Research*		*Middle*
Links between soil sealing and land take	*Lack of data on the degree of soil sealing associated with different land take processes and how it varies in different contexts (e.g., for the same land use class across different countries).*	*Knowledge development gap*			*Urban and industrial*			*Inconsistent definitions of land take and urban boundaries among countries hinder effective cross-country comparisons*	*Introduce standardised terminology*	*Innovation*	*Moderate*	*Short*
								Lack of consistent and accurate national measurements hinders land take and soil sealing assessments	*Develop nationwide studies that compare land take and soil sealing over the same period and that assess for distinct land uses the proportion of land take that has led to soil sealing*	*Research/ Innovation*		*Short*

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Knowledge gap	Short description	Type of KG	Sector					Bottlenecks	Actions			
			Agriculture	Forest	Urban and industrial	Nature	Multiple		Action	Type of action	Priority	Timeframe
Methods, indicators and data to monitor soil sealing and land take	*Lack of applicable methods, indicators and data to monitor soil sealing and land take processes at different scales (for example, in private gardens in urban context).*	*Knowledge development gap*			*Urban and industrial*			*There are diverse target audiences*	*Develop national soil monitoring programs will profit from an early involvement of stakeholders by promoting acceptance and shared interest in indicators, reference values and target values for soil quality, as well as from incorporation of practical knowledge on land management, service flow and the possibility to introduce payments for ecosystem services*	*Research*	*Low*	*Middle*
								Lack of conclusive results in research projects	*Research on monitoring and mapping soil sealing through remote/proximal sensing*	*Innovation*		*Middle*
								Different understanding of land take in various member states	*Introduce standardised terminology*	*Innovation*		*Short*
								High cost and effort to produce data from remote sensing/Earth Observation	*Identify robust data sources on soil sealing from remote sensing /Earth Observation*	*Innovation*		*Short*
								Lack of a cross-national agreement on a standard set of indicators	*Redefine and conceptualize common indicators to assess land take and soil sealing across European countries*	*Research*		*Short*
Lack of consistent approaches for monitoring soil sealing/land take across Member States	*Lack of understanding of the most effective procedures and indicators for monitoring soil sealing and land take across EU Member States.*	*Knowledge application gap*			*Urban and industrial*			*Lack of an integrated soil sealing and land take monitoring system at different scales*	*Exchange monitoring and mapping methods through initiatives (including networks, platforms, and research infrastructures) to further harmonise these methods throughout Europe*	*Innovation*	*Low*	*Short*
								Different methods can be applied	*Include and describe standardised methods in the Soil Monitoring Law*	*Research*		*Middle*
Quality of urban soils	*Lack of a systematic review of the current level of knowledge on the quality of urban soils.*	*Knowledge development gap*			*Urban and industrial*			*There are no consistent rules for completing and harmonizing the database of urban soil quality on an EU scale*	*Explore methods and develop effective tools to analyse soil quality*	*Research*	*Low*	*Short*
								Lack of data integration and standardization	*Densify the existing soil sampling networks in the EU (by integration of LUCAS with available national databases) and increase the soil parameters they collect to provide reliable data on soil quality*	*Innovation*		*Short*
Social acceptance of soil reuse	*Lack of social acceptance of soil reuse.*	*Knowledge development gap*			*Urban and industrial*			*Missing (not properly functioning) cooperation between research and Practice*	*Assess the current state of soil education in school curricula at all levels and monitor changes*	*Innovation*	*Low*	*Short*

DOI: 10.5281/zenodo.17430539

Supplementary materials for "Outlook on the knowledge gaps to reduce soil sealing and increase the reuse of urban soil"

Supplementary material 1

Overview of the knowledge gaps on soil pollution and restoration

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Data type: Qualitative.

Rank order	Knowledge gap title	Short description	Type of KG (Knowledge development gap, Knowledge application gap KDG and/or KAG)	Agriculture	Forest	Urban	Nature	Action	Type of action (Research, Innovation, R and/or I)	Timeframe (short-, medium-, long-term S/M/L)	**Bottlenecks**
1.	Impact on soils and soil ecosystem services	Significant knowledge gap exists concerning the impact of soil pollutants on soil characteristics, soil functions, ecosystem services and biodiversity. Large data gap exists on cocktail/mixture/cumulative/synergistic effects, including a general lack of knowledge on individual substances (presence and interactions in soil, transport and fate, mobility and persistence, ecotoxicological properties, bioaccumulation and bioavailability, exposure of and risk to the environment)	KDG and KAG	Yes	Yes	Yes	Yes	(i) Ambitiously enhance systematic monitoring of soil pollution, to fill in the extensive gaps on presence of pollutants in soils, (ii) Include in environmental risk-assessment long-term, low-level, chronic, cocktail/mixtures and cumulative/synergistic effects, feedback monitoring results in the authorisation of chemicals, as well as the indirect impacts, and impacts on landscape-level and ecosystem functioning/services, to integratively assess the impact on soil biodiversity and ecosystem services, (iii) Include all relevant independent studies in risk assessment, and ensure transparency, (iv) Research/action on prevention and remediation of soil pollution, e.g. transitioning to ecological farming methods and investing in nature-based solutions, (v) Include impact of soil pollution on ecosystem function/services in modelling to support policy making decisions, (vi) Enhanced research on individual substances (presence and interactions in soil, transport and fate, mobility and persistence, ecotoxicological properties, bioaccumulation and bioavailability, exposure of and risk to the environment)	(i) I (ii) R/I (iii) I (iv) R (v) I (vi) R	(i) S/M/L (ii) S/M/L (iii) S (iv) S/M (v) S (vi) S/M/L	1. The high complexity of soil and interactions of soil compounds, organisms and contaminants hinders the assessment of the full impact of soil pollution on the delivery of ecosystem services. 2. Lack of systemized monitoring, and limited capacity leads to data gaps which hinder the determination of the level and spatial extent of pollutants in EU soils, both for point-source and diffuse pollution 3. Various and varying attitudes and perceptions of actors involved in soil pollution hinder directing and attributing needed means and efforts to the identification and the assessment of the impact of soil pollutants and the extent of soil pollution.

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Rank order	Knowledge gap title	Short description	Type of KG (Knowledge development gap, Knowledge application gap KDG and/or KAG)	Agriculture	Forest	Urban	Nature	Action	Type of action (Research, Innovation, R and/or I)	Timeframe (short-, medium-, long-term S/M/L)	**Bottlenecks**
2.	Socio-economic and market tools	There is a need for a framework and more comprehensive tools reflecting on the relationship between soil pollution and the socioeconomic status of the polluter and those exposed to pollution, and the changes caused by preventive measures.	KDG and KAG	Yes	Yes	Yes	Yes	(i) Research addressing the intertwined nature of stakeholders' relationships and the effect of country specific cultural and historical backgrounds relevant to institutional, market, or policy setups and failures in the context of pollution prevention and the need for behavioural change; (ii) Comprehensive, consistent and comparative research of existing tools on socioeconomic issues, how both sides are affected by prevention, and how to fill data gaps; (iii) Further development and improvement of the tools; (iv)Testing the tools including the test of the TCA assessment in member states with contrasting levels of data to see how it performs under different circumstances, (v) making the socioeconomic impact of soil pollution and its prevention on the beneficiaries and on the negatively affected more transparent and to highlight trade-offs, (vi)Data collection on the socio-economic status of the exposed and the polluters, and the impact of the preventive measures on those statuses	(i) R/I (ii) R/I (iii) I (iv) I (v) I (vI) R	(i) S/MSL (ii) M (iii) S/M (iv) S (v) S/M (vi) S/M/L	1. Limited acknowledgement and understanding of the intertwined nature of stakeholders' (polluters and exposed to pollution) relationship hinder further development and improvement of the tools, and the identification of trade-offs. 2.Lack of cultural context hinders consistent data collection and comparison of data, and to develop adequate tools for addressing socioeconomic issues stemming from soil pollution prevention and remediations. 3. Sector-specific approaches hinder the development of an overarching, comprehensive and consistent framework for soil pollution prevention and remediation
3.	Impact on human health	Important research gaps remain on the impact of soil pollution on human health. There is a need for a full assessment of the 'exposome': the measure of all the exposures throughout a lifetime. Research needs include the assessment of cocktail/mixture and cumulative/synergistic effects, impacts of chronic low-level exposure and indirect effects (e.g. the impact of the loss of biodiversity and ecosystem services on human health).	KDG and KAG	Yes	Yes	Yes	Yes	(i) Ambitiously enhance systematic monitoring of soil pollution, to fill in the extensive gaps on presence of pollutants in soils(ii) Include in human health risk-assessment long-term, low-level, chronic, cocktail/mixtures and cumulative/synergistic effects (exposure to multicontaminants), as well as the indirect impacts though the impacts on e.g. ecosystem functioning/services, to integratively assess the impact on human health. Include the 'Exposome' in risk assessment.(iii) Include all relevant independent studies in risk assessment, and ensure transparency(iv) Research/action on prevention and remediation of soil pollution, e.g. transitioning to ecological farming methods and investing in nature-based solutions(v) Include impact of soil pollution on human health, including through the impact on ecosystem services, in modelling to support policy making decisions, (vi) Data collection and analysis of individual substances on human health (exposure routes, toxicological properties, the exposome)	(i) I (ii) R/I (iii) I (iv) R/I (v) R/I (vi) R	(i) S/M/L (ii) M/L (iii) S (iv) S/M/L (v) S/M (vi) S/M/L	1. The high complexity of soil pollutant mixtures and (indirect) effects on human health hinders systematic monitoring and health-risk assessment. Lack of systemized monitoring, and limited capacity leads to data gaps which hinder the determination of the level and spatial extent of pollutants in EU soils, both for point-source and diffuse pollution affecting human health. 3. The various and varying attitudes and perceptions of actors involved in soil pollution hinder the directing and attributing needed means and efforts to the assessment of the impact of soil pollution on human health and the development and application of preventive measures and remediation practices.

DOI: 10.5281/zenodo.17430539

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4.	Data gaps on soil pollution and lack of systemized monitoring	Despite the extensive knowledge on pollutants and their impacts a clear lack of data on soil pollution still exists, linked to a lack of systemized monitoring frameworks, which are needed to assess the scope and possible impacts of soil pollution, and to develop management and policy tools.	KDG and KAG	Yes	Yes	Yes	Yes	(i) review and comparative analysis of EU and national data on soil pollutions (existing and emerging pollutants); (ii) review of methodologies, and monitoring systems aimed at identifying site specificities (abiotic and biotic conditions), and shedding light on member state's priorities, economic, institutional, and regulatory constrains/ limitations; (iii) development of a monitoring framework and harmonisation of member states methodologies without hurting member states' interest and priorities by the standardization; (iv) establishment of an open access database on emerging pollutants to promote well-informed decision-making	(i) I (ii) I (iii) R/I (iv) I	(i) S/M (ii) S/M (iii) M/L (iv) S/M/L	1. Lack of standardised monitoring frameworks and methodologies for measuring pollutants hinders comparative analysis at EU level, the establishment and operation of consistent databases, robust risk assessment and well-informed decision-making. 2. High costs and institutional barriers hinder development of monitoring frameworks, harmonisation and comparative analysis.
5.	Technical/ practical tools to remediate soil pollution and restore soils	There is need for further development of remediation and restoration techniques, and for further knowledge on how traditional and alternative tools can be effectively and efficiently combined to meet set soil health targets for current and future potential land use. An important aspect is that legislation does not take into account all soil pollution and associated risks, leading to a lack of focus on remediation techniques which focus on tackling pollutant mixtures and emerging pollutants and on restoration. In practice, laboratory analytical programs often provide analysis only for those pollutants listed in the legislation. In this regard, there is a lack of a readily available open access database on new/state-of-the-art techniques/protocols, and new emerging pollutants, in order to support everyday decision-making on remediation.	KDG and KAG	Yes	Yes	Yes	Yes	(i) Research on the effect of mixtures and emerging pollutants; (ii) Research on how to improve efficiency and effectiveness of alternative techniques, including the review of how traditional and alternative methods could be combined; (iii) Review and comparative analysis of economic, institutional and policy framework of remediations and the technical solutions; (iv) Development and introduction of a coordinated mechanism and task on national and EU level to establish and maintain an open access database with a regular update of scientific research to support everyday decisions on remediation. (v) Review of the laboratory protocols and develop a procedure on how to update them for emerging pollutants	(i) R (ii) R/I (iii) I (iv) I (v) I	(i) S/M/L (ii) M/L (iii) S/M (iv) S/M/L (v) S	1. Nature-based solutions are often time-consuming which hinders their further development and application, as well as the development and uptake of nature-based solutions in combination with traditional methods and techniques. 2.Limited market interest for alternative remediations solutions hinders research and development of alternative methods. 3. Outdated laboratory practices hinder the adoption of new techniques and the assessment of the effect of pollutant mixtures and emerging pollutants.

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6.	Behaviour/ transportation and fate of soil pollutants and link of soil pollution with water and air	Soil pollution contributes to water and air pollution, and pollutants transported by air and water can cause soil pollution, particularly diffuse pollution. Extensive knowledge gaps exist concerning the partitioning of pollutants in different physical phases, and the behaviour, transportation and fate of many soil pollutants in soil, water and air. These three compartments hence need to be adequately assessed to evaluate (the impact of) diffuse soil pollution, demanding complex analysis.	KDG and KAG	Yes	Yes	Yes	Yes	(i) New research and research update on the partitioning of pollutants in different physical phases, and the behaviour, transportation and fate of existing and emerging soil pollutants in soil, water and air taking into account site specific characteristics; (ii) Comprehensive and comparative review of human activities' impact on soil pollutant's move among the three compartments, (iii) Comparative review of the existing decision support systems to assess their ability to promote preventive decision making	(i) R/I (ii) I (iii) I	(i) S/M/L (ii) S/M (iii) S/M	1. Institutional barriers (e.g. lack of personnel and laboratory facilities) hinder new research and research updates on pollutants' characteristics and partitioning in different matrices.
7.	Baseline, Indicators/ descriptors and quality thresholds/ criteria	There is a need for baselines and environmental quality standards for the assessment and monitoring of soil health. Natural background concentrations and natural variability of soils, the physical and chemical state, and soil biodiversity are relevant in this regard. Detailed soil monitoring data are missing. Soil health descriptors and accompanying quality thresholds should be established, including a robust set of biodiversity indicators, to allow for systematic and high quality monitoring and soil health assessment.	KDG and KAG	Yes	Yes	Yes	Yes	(i) Review and comparative analysis of the baselines with consideration given to site specificity and natural contamination level; (ii) Gather knowledge on expectation abundances and diversity of in-soil biodiversity - start with earthworms and develop of indicators and criteria for determining chemical and biological soil health in view of soil diversity; (iii) Review and development of environmental quality standards for monitoring and soil biodiversity	(i) R (ii) R/I (iii) R/I	(i) S/M/L (ii) S/M (iii) S/M	1. Ambiguity of definition of soil health and its indicators hinders comparative analysis and establishing clear baselines, and harmonizing environmental quality standards and targets.

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8.	Overall impact of soil pollution on wider ecosystem functioning	The relationship between soil pollution and ecosystem functioning is not fully understood and/or acknowledged, partly due to insufficient available data. Thus there is a lack of a framework that addresses the aspects related to the link between soil pollution, prevention and ecosystem functioning in a spatiotemporal context. Soil functions play a key role in why and how soil pollution affects ecosystem functioning. While that role has been extensively researched in a sector specific context, there is a lack of a holistic approach that simultaneously focusses on soil pollution and prevention/remediation/restoration choices.	KDG and KAG	Yes	Yes	Yes	Yes	(i) Research on the links between soil pollution and ecosystem functioning; (ii) Review and update the existing data in order to establish the relationship between pollution and ecosystem functioning; (iii) Development of a comprehensive analytical framework to address spatiotemporal economic, institutional and policy failures and identify decision making levels in order to reach prevention of pollution, (iv) Systematic monitoring of changes in ecosystem functioning due to soil pollution and/or prevention measures including restoration and remediation.	(i) R (ii) I (iii) R/I (iv) R	(i) S/M/L (ii) S (iii) S/M (iv) S/M/L	1. Differences in stakeholders' perception on the relationship between soil pollution and ecosystem functioning and on the need for a holistic approach hinder prevention oriented policy development and decision making. 2. Sectoral interests related to soil pollution and prevention lead to policy fragmentation and contradiction, along with disproportionate allocation and/or distortion of financial resources and hinder the implementation of prevention oriented policies. 3. Differences in level of detail, sources (different sectors, spatial and time scales, ...) and structure of data hinder a holistic and overarching framework addressing the impact of prevention of soil pollution and remediation on ecosystem functioning.
9.	Technical/practical tools to prevent agricultural soil pollution	While a wide array of agricultural management practices exist to reduce/minimise soil pollution and restore soil health, there is still a high need to further develop and optimise sustainable soil management practices for all relevant EU cropping systems and pests. Research areas include Integrated Pest Management, Agroecology, Agroforestry, biocontrol, regenerative farming, monitoring technology and mechanical pest/weed management.	KDG/KAG	Yes				(i) Research on IPM, agroecological, agroforestry, and regenerative and conservation practices, to optimise IPM for all relevant EU crops/pests, and to assess all benefits of IPM at landscape-scale level, in framework of soil health, soil and aboveground biodiversity and ecosystem services(ii) Research on biocontrol measures, to extend biocontrol options for a wider variety of pests and cropping systems.(iii) Research on technology/robotics to enhance monitoring of pests/crop health/soil health and mechanical weeding(iv) Further expanding, connecting and coordinating living labs, lighthouses and regional networks working on IPM, agroecology, agroforestry, conservation/regenerative agriculture, ... to expand testing of sustainable agricultural practices, which minimise or eliminate soil pollution and effectively restore soils(v) Research on 'system innovation', 'system shifts', and the design of alternative cropping and farming systems at regional/landscape level which effectively reduce soil pollution and restore soils	(i) R /I (ii) R/I (iii) R/I (iv) I (v) I	(i) S/M/L (ii) S/M/L (iii) S/M/L (iv) S (v) S/M	1. Diversity in cropping systems, pests, and conditions and farming systems in the EU challenges the development of preventive measures for all farming systems and environmental conditions. 2. Lack of effective implementation and enforcement of environmental legislation and effective spending of public funds, leading to a lack of clear incentives, drivers and obligations for further development and optimisation of sustainable cropping practices. 3. Fragmentation of projects, initiatives and networks working on sustainable agricultural soil management practices hinders the shift to wide implementation of soil health and prevention oriented agricultural practices. 4. Conflicts of interests between e.g. agrochemical companies and further development and optimisation of agronomic practices minimising inputs/soil pollution hinder the implementation of preventative and soil health oriented policies.

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10.	implementation of measures to prevent agricultural soil pollution	While a wide array of agricultural management practices exist, their wide implementation and uptake is lacking. Different knowledge gaps still exist on how to implement these practices much more widely, taking into account socio-economic drivers, availability of a supportive framework (knowledge/advisory services, policy, public funds, insurance systems) and practical long-term implementation.	KAG	Yes				(i) Research on the effective implementation of IPM, agroecology and sustainable soil management practices (ii) Invest funds in the further development, coordination, expansion and connection of regional networks of farmers/lighthouses/living labs working on the practical implementation of sustainable agronomic practices (iii) Research on needed policy action/ implementation/enforcement to ensure alignment of policies and public funds with environmental objectives (iv) Foster the development of independent advisory systems throughout Europe, through the creation of active, living knowledge sharing networks on best available (implementation) practices (v) Research on the development of crop- and sector- specific IPM rules, based on scientific expertise and best available practices, to ensure the effective implementation of IPM (vi) Further develop a toolbox with best available IPM, agroecological and sustainable soil management practices (vii) Research on key socio-economic drivers, including on insurance mechanisms and integration/inclusion of the whole food chain, to ensure the effective uptake of sustainable soil management practices/IPM.	(i) R /I (ii) I (iii) R/I (iv) I (v) R/I (vi) I (vii) R/I	(i) S/M (ii) S/M (iii) S/M (iv) S/M/L (v) S/M (vi) S (vii) S/M	1. Lack of effective implementation/ enforcement of current legislation and lack of linkages between environmental objectives and public funding hinder changes and shift towards wide implementation of soil health and prevention oriented agricultural practices. 2. Fragmentation of legislation at both national and international level and of existing initiatives (projects, EU/regional networks/national/ local networks, …) focused on the implementation of sustainable agronomic practices lead to inefficient allocation of resources and hinder shift to prevention and soil health oriented agricultural practices. 3. The complexity of the food chain, and accompanying challenges in involving the whole food chain in fostering and ensuring the implementation of sustainable soil management, hinder the shift to soil health-oriented agricultural practices. 4. Lock-in mechanism of agricultural soil pollution (e.g. farmers' perception and views on soil pollution, then existing framework of input providers, farmers, processing industry and retail, the current system of allocation of agricultural funding, …) hinder the implementation of prevention and soil health oriented agricultural policy.

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Other identified Knowledge gaps											
	Tools to prevent non-agricultural soil pollution	Which technical tools are available to prevent non-agricultural soil pollution, and which are missing?									
	Lack of modelling tools	Lack of modelling tools to evaluate in an integrative way the impact of reducing soil pollution (e.g. pesticide use) on the delivery of ecosystems services, and linked economic impact									
	Which stakeholders are affected	Which stakeholders are affected by soil pollution?									
	Impact on stakeholders	How are stakeholders affected by soil pollution? (e.g. health, overall well-being, economically, land use)									
	Impact of stakeholders	How do stakeholders impact soil pollution, land use policy, research and innovation?									
	Benefits for stakeholders	How would different stakeholders benefit from decreased soil pollution?									
	Policy tools to prevent soil pollution and their fitness-for-purpose	Which policy instruments are in place, under way and still needed to prevent soil pollution? Are current/underway tools fit for purpose?									
	Lock-in mechanisms of soil pollution	Which lock-in mechanisms of soil pollution currently exist, and how can these be tackled? (e.g. current funding of Common Agricultural Policy, attitude and perception of stakeholders, advisory systems, food chain mechanisms)									

DOI: 10.5281/zenodo.17430539

Supplementary materials for "Outlook on the knowledge gaps to reduce soil erosion"

Supplementary material 1

Table 2 -

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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.

Table 2. The total amount of knowledge gaps identified and details about each one.

	Knowledge gap	Short description	Type of KG	Sector					Bottlenecks	Actions		Priority	Timeframe
				Agriculture	Forest	Urban and industrial	Nature	Multiple		Action	Type of action		
1	Co-construction of soil erosion prevention techniques and field strategies with practitioners	To 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	Knowledge Application Gap	X	X	X	X			Promote regenerative and conservation agriculture as a means to systematically organize soil erosion control measures	Innovation	High	
										Nature-based solutions (NbS) which are evidence-led, locally appropriate, targeted at soil erosion hotspots and their off-site effects	Innovation		
										Identification, characterization and assessment of NbS projects	Research		
										Participatory monitoring and assessment of NbS and regenerative land use impacts	Innovation		
										Collaborative approaches to collect accurate, spatially distributed data on soil erosion	Innovation		
										Dedicated demonstration sites for conservative and regenerative measures	Innovation		
										Financial support for practitioners to implement conservative and regenerative practices	Innovation		
										Testing new measurement approaches (integration of remote sensing-based innovation and technology that allows for upscaled estimates)	Research		

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	Knowledge gap	Short description	Type of KG	Sector					Bottlenecks	Actions		Priority	Timeframe
				Agriculture	Forest	Urban and industrial	Nature	Multiple		Action	Type of action		
2	Co-developing tools that can support managers' and landowners' decision making	Understanding managers' and landowners' motivations during land management is critical, and collaborative approaches and governance mechanisms need to be developed jointly for informed and effective decision-making	Knowledge Application Gap	X	X	X	X			Understanding land managers and landowners' motivations during land management	Research	High	
									Lack of soil literacy among land managers and policy makers hinders the recognition and assessment of soil health related to local contexts and soil types	Joint development of collaborative approaches and governance mechanisms	Innovation		
										Testing already existing co-developed tools with a broader range of end users	Innovation		
										Build skills and knowledge in recognizing and assessing soil health	Innovation		
3	Representation of ecosystem services' losses following soil 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	Knowledge Development Gap	X	X	X	X			Create/reinforce funding specifically directed to assess linkages between environmental losses (ES) resulting from soil erosion and economic costs	Research	High	
										Develop a functional contractualization system and fair mechanisms for attractive rewarding incentives to reduce speculative and unsustainable land use	Innovation		
4	Soil erosion risk maps	The need of soil erosion risk maps encompassing various types of soil erosion, including potential mitigation and restoration measures, is indispensable for anticipating when and where soil erosion might occur at unsustainable rates, therefore providing valuable evidence-based information for policy- and decision-making	Knowledge Application Gap	X	X	X	X			Integrating sediment connectivity modelling in soil erosion risk maps, supported by empirical data	Research	Moderate	
										Explore Artificial Intelligence and machine learning models to enhance the accuracy and adaptability of soil erosion risk maps	Research		
										Build erosion prediction scenarios that provide information on the magnitude of consequences, including off-site effects and subsequent risk management	Research		
									Variability in methodologies, which complicates meaningful comparisons and hinders effective policy applications	Development of a sound delimitation methodology and effective norms regarding authorized land use and monitoring	Research		
5	Interactions between natural and anthropogenic soil erosion processes, and societal impacts	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	Knowledge Development Gap	X	X	X	X			Research on interactions operating across diverse spatial and temporal scales, with an emphasis on predicting rates and assessing onsite and off-site impacts	Research	Moderate	
										Interdisciplinary research linking soil erosion processes with societal impacts	Research		

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	Knowledge gap	Short description	Type of KG	Sector					Bottlenecks	Actions		Priority	Timeframe
				Agriculture	Forest	Urban and industrial	Nature	Multiple		Action	Type of action		
6	Establishing a Soil Erosion Monitoring Network at the EU level, including long-term experimental sites	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. 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	Knowledge Development Gap	X	X	X	X			Development of long-term experimental sites	Innovation	Moderate	
7	Raise awareness about soil erosion and its impacts	Need to increase awareness of soil erosion and the potential threats it poses, namely by developing a comprehensive guide on the importance of soil, the risks associated with soil erosion, impacts on life on Earth and ecosystem services	Knowledge Application Gap	X	X	X	X		Lack of awareness of the importance/ urgency of preventing soil erosion hinders the adoption of an informed and proactive approach to soil management	Create a soil health certificate	Innovation	Moderate	
8	Setting benchmarks for soil health	Setting benchmarks for soil health, where soil health objectives and indicators are established to be actionable across various policy domains and sectors, including the development of benchmarking tools to be used by farmers, which are practical, accurate and sensitive to regional differences and variation across time periods	Knowledge Development Gap	X	X	X	X			Development of practical, regionally-sensitive benchmarking tools	Research	Moderate	
9	Scientific evidence of potential benefits and context-specific trade-offs of Nature.based solutions	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	Knowledge Development Gap	X	X	X	X			Research on qualitative understanding of the trade-offs and benefits of NbS	Research	Moderate	
										Gather evidence on the effectiveness of soil bio-engineering techniques in more contexts, and robust cost-benefit analyses	Research		
10	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	Knowledge Development Gap	X	X	X	X		Soil erosion rates can vary depending on the measurement technique and spatial scale, leading to challenges in calibrating models across different landscape contexts	Developing multi-scale approaches that combine field-scale erosion data with high-resolution techniques	Research	Moderate	
										Research on the connectivity of erosion factors across spatial and temporal scales	Research		
										Research on the interactions of socio-economic and cultural drivers leading to tipping points for erosion processes	Research		

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	Knowledge gap	Short description	Type of KG	Sector					Bottlenecks	Actions		Priority	Timeframe
				Agriculture	Forest	Urban and industrial	Nature	Multiple		Action	Type of action		
11	Assessment of sediment redistribution	To comprehensively quantify soil erosion, the assessment must extend beyond merely on-site effects and include the wider repercussions of sediment redistribution	Knowledge Develop-ment Gap	X	X	X	X					Low	
12	Scale effect and related implications of soil erosion phenomena	The scale effect in un-derstanding phenomena related to soil erosion, and its implications for multiple ecological processes, must be addressed in the future	Knowledge Develop-ment Gap	X	X	X	X					Low	
13	Connectiv-ity of slope gradient and aspect, rainfall and wind intensity, soil type, management practices, and natural events across spatial and temporal scales	The dynamics of factors such as slope gradient and aspect, rainfall and wind intensity, soil type, management practices, and natural events have been individually asso-ciated with triggering soil erosion. However, the connectivity of these factors across spatial and temporal scales remains poorly comprehended	Knowledge Develop-ment Gap	X	X	X	X					Low	
14	Interactions of socio-eco-nomic and cultural drivers	Understanding of the interactions of socio-eco-nomic and cultural drivers, including policy drivers, leading to tipping points for erosion processes is also lacking	Knowledge Develop-ment Gap	X	X	X	X					Low	
15	Tools to integrate soil erosion risk maps with economic and ecological effectiveness analyses	Developing tools that seamlessly integrate the aforementioned soil erosion risk maps and potential mitigation, or restoration solutions combined with economic and ecological effectiveness analyses	Knowledge Develop-ment Gap	X	X	X	X					Low	
16	Effects and trade-offs of land manage-ment prac-tices, water management and climate change	The effects and trade-offs of land management practices, water manage-ment (including irrigation and drainage), and climate change (including green-house gas emissions, increased freezing and thawing events) remain inadequately understood	Knowledge Develop-ment Gap	X	X	X	X					Low	
17	Comparison of soil erosion rates among different types of fires or along soil burn severity gradients	Comparing soil erosion rates among different types of fires (pastoral, prescribed, wildfires) or along soil burn severity gradients is an increasing-ly urgent need	Knowledge Develop-ment Gap	X	X		X					Low	
18	Calibration and validation of existing models	Calibration and validation of existing models are required, emphasizing 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	Knowledge Develop-ment Gap	X	X	X	X					Low	

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	Knowledge gap	Short description	Type of KG	Sector					Bottlenecks	Actions		Priority	Timeframe
				Agriculture	Forest	Urban and industrial	Nature	Multiple		Action	Type of action		
19	Identification of trade-offs between policies	It is imperative to identify trade-offs between policies and to test strategies to mitigate them	Knowledge Development Gap	X	X	X	X					Low	
20	Effective transference of soil erosion techniques after fires	Transferring knowledge on soil erosion techniques after fires requires careful consideration as its effectiveness and widespread dissemination have been limited	Knowledge Application Gap	X	X		X					Low	
21	Planning monitoring systems in a cost-effective manner	Planning monitoring systems in a cost-effective manner to ensure their endurance in the future	Knowledge Application Gap	X	X	X	X					Low	
22	Allocate resources to experts and expertise on integration	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.	Knowledge Application Gap	X	X	X	X					Low	
23	Measures to mitigate negative trade-offs between policy instruments	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	Knowledge Application Gap	X	X				Lack of harmonization between policies due to the complexity of the subject	Reform policy to drive farmers to take care of soil health and in parallel create training to secure farmers' know how	Innovation	Low	
24	Test Results-based models within CAP	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.	Knowledge Application Gap	X					Negative perception of environmental policies	Soil Health Results-based models transversal to land use	Research	Low	

DOI: 10.5281/zenodo.17430539

Supplementary materials for "Outlook on the knowledge gaps to improve soil structure"

Supplementary material 1

Overview of the knowledge gaps

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Data type: Qualitative

Knowledge gap	Short description	Type of knowledge gap	Sector					Bottlenecks	Actions		Priority	Timeframe
			Agriculture	Forest	Urban/ industrial	Nature	Multiple		Action	Type of action		
How can we manage and adapt soil structure to support effective water regulation and habitat provision across scales—from microhabitats to catchment areas—in the face of climate change and evolving land-use practices?	Will the changing climate and, management options have an impact on what is considered optimal soil structure now? Should restoration of soil target to original soil structure or condition that enables provision of ecosystem cervices? How big of a change is needed for soil structural functioning to improve?	Knowledge development gap, Knowledge application gap					What constitutes an optimal soil structure for sustaining ecosystem services prioritized in the land-use or land area in question			Research action, Innovation action	High	Short-term
How can we quantify and value soil structure to support sustainable land management, economic assessments, and predictive modeling across scales and applications?	What is the best measure for good soil structure at relevant scales (micron, pedon, country to continental scale)? How can we measure the soil structure for various purposes and scales, and to produce future scenarios and impact assessments (models)	Knowledge development gap						Lack of common indicators, Methods not harmonized		Research action, Innovation action	High	Short-term
How do biological, physical, and chemical factors in soil interact to build and maintain its structure, and how can management practices harness these interactions to enhance soil structural resilience or restore it after deterioration?	What is the relationship and relative importance of soil physico-chemical properties and biological builders of soil structure in different environments? What extent can crop stands impact soil structure? What are the possibilities to maintain or improve soil structural functioning with in-depth knowledge on soil biology? What is the importance of soil macrofauna for soil structure formation and manintenance across Europe? How changes in management or environmental conditions affect soil structure by impacting soil biota and biodiversity; Can we detect key species related to soil structure?							Lack of interaction among research, advisory services and land managers		Research action	High	Short-term
How forest management (timber extraction, soil preparation) and other disturbances (forest fires) effect soil structure and what are the off-site effects (e.g. flooding)?										Research action	Moderate	Midterm

DOI: 10.5281/zenodo.17430539

Knowledge gap	Short description	Type of knowledge gap	Sector					Bottlenecks	Actions		Priority	Timeframe
			Agriculture	Forest	Urban/ industrial	Nature	Multiple		Action	Type of action		
Impact of circular economy and soil improvement materials in maintaining or improving soil structure in changing environment	A circular bioeconomy promotes the re-use of processed raw materials and is a step forward from the current linear economic system in which materials are discarded after they are used. This circularity may change the material flows and quality used and ending in soils. More information and knowledge sharing is needed to enhance the circular economy.	Knowledge development gap, Knowledge application gap								Research action, Innovation action	Moderate	Short-term
How is a changing climate and operational/ business environment challenging current management practices, and what impact will it have on soil structure if these practices are maintained or adjusted to the changing environment?	How possible changes in food production (regional distribution, crops, production sector, farm size) and consumption will affect soil structure and functioning in the future?									Research action, Innovation action	Moderate	Short-term
How to increase the interest towards soil structure and knowledge on the role of soil structure (especially sub soil) on water management among the land-managers? How to help farmers and land managers to avoid management-induced soil structure?										Research action, Innovation action	Moderate	Long-term
How much the soil has compacted, and can the soil recover from compaction? Soil sealing and the effect on soil structure, can the soil recover from sealing?							Relative rarity of the final aim/ comparison target that is natural soil profiles in Europe (big anthropogenic influence, no pristine soil)			Research action	Low	Mid-term
Supply chain pressure: How to get better contracts for the farmers so that the contracts don't put you in field at the wrong time?										Research action	Low	Long-term
Does soil classification based on soil texture loose the information needed for soil structure management? (soil classification based on soil forming processes?)												

DOI: 10.5281/zenodo.17430539

Supplementary materials for "Outlook on the knowledge gaps the EU global footprint on soils"

Supplementary material 1

Table 2 - Roadmap overview

Author: Eric Struyf, Ivan Janssens, Vincent Dauby, Orsolya Nyárai, Péter László, Dries Roobroeck, Gerdts Detlef, Ellen Fay, Gerry Lawson, David Robinson, Arwyn Jones, Mathis Wackernagel

Data type: Qualitative.

Knowledge gap	Short description	Type	Agriculture	Forest	Urban/industrial	Nature	Multiple	Bottlenecks	Action	Priority	Time
1	We do not have solid knowledge on the KEY IMPACT AREAS of food and fibre input into the EU, yet this is crucial to enable to most effective solutions to reduce the footprint.	Knowledge gap					x	Variety of sources and methods to defining key value chains and associated land impact. Multiple footprint definitions.	Detailed global map of import of food and fibre commodities into the EU needs to be produced, by providing a total inventory of potential impacted soil surfaces per commodity, per impact region	High	Medium-term
								How to handle trade-offs between multiple ecosystem services. No ready-to-use tool to match land impact to multiple soil ecosystem services	Global map linked to known effects of agricultural, forestry and agro-forestry activity on soil's provision of ecosystem services, both negative and positive, to achieve theoretical soil impact		
								Current approaches mostly useful for large scale, broad sectoral approaches	Link theoretical footprint map to observations for validation		
									Define key impact areas		
2,3	We need a harmonized and regionalized soil health assessment methodology, incl. trade-offs. We need to disentangle food and fibre impact from other impact	Knowledge implementation gap					x	No uniform standardized datasets are available on soil footprints	An overall framework should be available of key soil ecosystem services to assess, and how to assess them, for outside EU soil footprinting. This can build also on soil targets envisaged in EU Nature Restoration Law	High	Short-term
								Even within EU, difficult to agree on standardized and obligatory soil monitoring	Install a solid on-the-ground monitoring of effective soil impact related to export of key agricultural commodities to the European Union. Potential to build on JRC soil quality index used in EMAS schemes		
								Agreement on key soil ecosystem services difficult to achieve, also due to different impacts depending on commodity, region and sustainability of practices			

DOI: 10.5281/zenodo.17430539

Knowledge gap	Short description	Type	Agriculture	Forest	Urban/industrial	Nature	Multiple	Bottlenecks	Action	Priority	Time
4	We need to assess potential of other EU footprinting and beyond EU impact initiatives for soils	Knowledge implementation gap					x	CBAM currently not linked to agriculture and focused only on carbon footprint	Synthesize knowledge on soil impact already available from other impact actions such as EUDR and CBAM, including also voluntary approaches, including Rainforest Alliance and Roundtable on Sustainable Palm oil.	High	Short-term
								EUDR shows complexity of traceability of geographic impact actions, particularly for commodities sourced from multiple smallholders and mixed production systems.	Need to define short-term realistic goals (probably linked to other footprint actions) and long-term ambitious goals		
								Large variety of 'voluntary mechanisms' for reducing soil footprint, all with own specific focus.	Need for direct accounting of outside EU impact in any proposed action within other soil EU missions.		
								Complexity currently experienced in other actions for implementation (e.g. EUDR) will be multiplied in soil initiatives, due to broad scope			
5	We need to define spill-over effect of EU Green Deal and other EU actions, decisions, policy	Knowledge gap					x	Other EU soil mission objectives focused on within EU actions, not accounting for outside EU impact.	Need for direct accounting of outside EU impact in any proposed action within other soil EU missions.	High	Medium-term
								Risk to shift the burden of governance and capacity building to producing countries			
								EU's role in driving demand for e.g. deforestation linked products not sufficiently linked to overconsumption and market power imbalances			

DOI: 10.5281/zenodo.17430539

Supplementary materials for “Outlook on the knowledge gaps related to soil literacy”

Supplementary material 1

Soil Literacy Knwoledge gaps overview 2025

Author: Roger Roca Vallejo, Anna Krzywoszynska, Loukas Katikas, Karen Naciph Mora, Marie Husseini, Sónia Morais Rodrigues, Roos van de Logt, Karen Johnson, Borut Vrščaj, Camilla Ramezzano, Katja Črnec and Almut Ballstaedt

Data type: Qualitative

				Sector									
Knowledge Gap Title	Knowledge gap description	ABC Classification	Type of knowledge gap	Agricul-ture	Forest	Urban/ industrial	Nature	Multiple	Bottlenecks	Action	Type of action	Priority	Timeframe
Factors influencing soil conservation measures adoption	"More research is needed to promote understanding of the key factors that enable and/ or prevent forestres, farmers, urban planners, civil engineers and other actors to consider soil health and to adopt soil conservation practices."	B	"Knowledge Development Gap"			"All			The singularities of local contexts hinder the possibility of making generalisations.	"Conduct surveys and interviews with farmers to identify motivations and barriers to adoption."	"Research"	"High"	"To be discussed"
Pathways linking soil knowledge and stewardship	"More research is needed in fostering the connection between soil science knowledge and soil stewardship. Instead of focusing on why the gap exists (soil stewardship paradox), studies should explore how, where, and when soil knowledge contributes to responsible soil care."	A, C	Knowledge Development Gap			"All			"Difficulty in measuring changes in attitudes and behaviors over time causes a lack of understanding of the progress in soil literacy imrprovement"	Engage experts in psychology, sociology, and education to understand the factors influencing responsibility and care.	Research	"High"	"To be discussed"
										Analyse successful soil stewardship models globally to identify effective strategies for bridging knowledge and action gaps.	Research		
Pedagogical strategies for soil literacy	"More research is needed on the development of effective pedagogical strategies to foster a deeper understanding of soil's importance. These strategies should promote critical thinking and be state-of-the-art, hands-on and experiential."	"C"	"Knowledge Application Gap"			"All			"Limited training for teachers hinders the implementaiton of new pedagogical strategies. Regulation and political barriers hinder curriculum development. The depth of soil science education often depends on individual teachers' interests and experiences, as well as available resources to meet educational standards set by authorities. The disconnection between fundamental soil science knowledge and practical environmental and industrial applications causes lack of interest. The often-used outdated lecture format hinders engagement and understanding in soil science education. Outdated textbooks and delayed updates in soil classification hinder effective soil science education globally, limiting knowledge transfer to students."	Develop case studies that illustrate successful integration of soil health in various curricula.	Innovation	High	"To be discussed"
										Pilot hands-on learning modules in schools and gather feedback for improvements.	Research		
										Collaborate with educators to share best practices and resources.	Innovation		
										Foster collaborations between high schools and universities, promote practical exercises like field activities, and use technology tools.	Innovation		

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Knowledge Gap Title	Knowledge gap description	ABC Classification	Type of knowledge gap	Sector: Agricul-ture	Sector: Forest	Sector: Urban/ industrial	Sector: Nature	Sector: Multiple	Bottlenecks	Action	Type of action	Priority	Timeframe
Inclusive soil education across learning needs	"More research is needed in creating educational materials tailored to different educational levels and neurodivergent people to encourage student interest, curiosity and engagement."	"C"	"Knowledge Application Gap"	"All					Resistance from educators to change established curricula hinders a more effective and inclusive soil health education. Comprehensive curriculum evaluations across different educational levels are time consuming and require a high level of organisation across staff and the sub-national bodies. Teachers limited formal training on soil science hinders the education quality underscoring the need for improved teacher preparation. Difficulty in measuring the effectiveness of curriculum improvements over time supposes a challengue in tracking the improvement in soil literacy levels.	Conduct evaluations of current school curricula to assess their effectiveness in teaching soil science.	Research	"High"	"To be discussed"
										Develop recommendations for curriculum improvements based on evaluation findings.	Innovation		
										Emphasize successful examples of soil improvement to foster a more accurate perception among young people about the potential for solving soil degradation problems.	Innovation		
										Collaborate with educators to implement and test curriculum changes.	Innovation		
Incentives for innovative soil teaching practices	"More research is needed to identify the key factors that stimulate instructors to adopt new and inspiring teaching methods with regard to soil education."	"B, C"	"Knowledge Development Gap"	"All					Institutional resistance to change established teaching practices. Lack of awareness about the benefits of new teaching methods.	Develop professional development programs that provide incentives for adopting innovative teaching practices.	Innovation	High	"To be discussed"
										Collaborate with educational institutions to pilot new methods and evaluate their effectiveness.	Innovation		
										It is crucial to provide primary and secondary teachers with training that enhances their comfort and competence in teaching basic soil science concepts.	Innovation		
Influence of local contexts on the outcomes of citizen science in soil health	"More research is needed in assessing how local conditions affect the long-term success of citizen science initiatives in soil health, in terms of scientific data collection and public education goals and other outcomes."	"B, C"	"Knowledge Development Gap"	All					"Variability in local policies and regulations may complicate studies. Difficulty in accessing data across different jurisdictions. Stakeholder disinterest and unstable group dynamics hinder participatory modeling, with sporadic participation reducing engagement and diversity in discussions."	"Conduct comparative studies in different urban contexts to identify key factors affecting soil health initiatives."	"Research"	"High"	"To be discussed"
Integrating soil into education for sustainable development competence models	"Further research is required to develop and validate frameworks that integrate soil as core component into Education for Sustainable Development (ESD) competence models."	"C"	"Knowledge Application Gap"	All					"Insufficient emphasis on soil in sustainability education hinders effective learning and awareness. Long cycles of national curriculum reviews causes delay of the reform and inclusion of soil science in educational subjects."	"Conduct workshops for educators on using soil as a teaching tool for sustainability concepts."	"Innovation"	"High"	"To be discussed"

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Knowledge Gap Title	Knowledge gap description	ABC Classification	Type of knowledge gap	Sector: Agricul-ture	Sector: Forest	Sector: Urban/industrial	Sector: Nature	Sector: Multiple	Bottlenecks	Action	Type of action	Priority	Timeframe
Using cultural and social aspects to improve soil health communication	"More research is needed in improving soil health communication strategies that prioritise cultural and social aspects of soils significant to diverse actors."	A, B, C	"Knowledge Application Gap"	All					"Difficulty in reaching diverse types of actors hinders effective stakeholder engagement processes. Overly technical soil science education hinders the engagement of non-experts and general audiences. In many developed countries, food abundance and the diminishing agricultural workforce have caused public apathy regarding soil understanding and protection. A focus on immediate crises and the gradual, non-urgent nature of soil degradation among policymakers hinders the prioritisation of soil-related concerns."	Develop educational materials that reflect cultural and social contexts related to soil.	Innovation	High	To be discussed
										Long-term communication strategies should illustrate the costs and benefits of soil degradation and protection measures.	Innovation		
										Example: The Spanish Society of Soil Science has initiated various soil contests for students, emphasizing ongoing engagement with the target audience, recruitment for collaborations, continuous development of educational resources, and training in science communication for soil scientists.	Innovation		
										Example: With techniques relating to stand-up comedy, and with soil science societies, we created the 'Soil Profile of the Month' online blog on the website of the Soil Science Society of Belgium.	Innovation		
Understanding Soil-Based Ecosystem Services for Targeted Stakeholder Communication	More research is needed in understanding the ecosystem services delivered by soils for key actor groups to improve targeted communication.	C	Knowledge Development Gap	All					Limited access to soil services data across different regions hinders comprehensive understanding and action	Collaborate with local governments to promote soil service assessments in land use planning.	Innovation	High	"To be discussed"
Evaluating the Effectiveness of Soil Health Outreach in Education and Recruitment	"More research is needed in evaluating the effectiveness of outreach efforts aimed at engaging primary and secondary school students, as well as the general public, in soil health topics and their impact on attracting new students to university-level soil health programs."	B, C	"Knowledge Development Gap"	All					"Limited capacity to measure long-term outreach impacts hinders the ability to assess and improve program effectiveness. Institutional resistance to prioritizing soil science programs hinders progress in soil education and capacity building. Student interest in sustainability grows, but soil science's traditional focus on agriculture hinders its environmental relevance in education."	"Conduct evaluations of outreach programs targeting school students to assess their effectiveness."	"Research"	High	To be discussed
NA	"More research is needed in assessing teaching approaches, content, and outcomes of soil health courses across institutions."	"C"	"Knowledge Development Gap"	All					"Difficulty in achieving consensus on definitions across diverse groups."	Collaborate with stakeholders to promote the adoption of standardized terminology.	Innovation	Low	To be discussed
										Develop educational resources that clarify soil health concepts for various audiences.	Innovation	High	

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Knowledge Gap Title	Knowledge gap description	ABC Classification	Type of knowledge gap	Sector					Bottlenecks	Action	Type of action	Priority	Timeframe
				Agricul-ture	Forest	Urban/ industrial	Nature	Multiple					
NA	"More research is needed in defining key terms like ""soil health"" and Soil Mission Objectives to create a common understanding across disciplines."	C	"Knowledge Development Gap"			All			"Difficulty in achieving consensus on definitions across diverse groups."	Collaborate with stakeholders to promote the adoption of standardized terminology.	Innovation	High	To be discussed
										Develop educational resources that clarify soil health concepts for various audiences.	Innovation		
NA	"More research is needed in analysing how scientists, policymakers, and businesses communicate in soil health projects beyond the 'top-down vs. bottom-up' model."	B, C	"Knowledge Development Gap"			All			"Difficulty in accessing data on communication practices across sectors."	Analyse communication practices in soil science projects across various sectors.	Research	Low	To be discussed
										Develop guidelines for effective communication among diverse stakeholders in soil science.	Innovation		
NA	More research is needed in understanding how different actors perceive and value soil health based on their needs, values, and cultural backgrounds.	A	Knowledge Development Gap			All			Difficulty in measuring changes in awareness over time.	Consultation with academics, industry, and professionals, by means of online (Delphi Study) and face-to-face forums.	Research	Medium	To be discussed
NA	More research is needed in examining how long-term national curriculum review cycles delay soil health education reforms and innovations.	B, C	"Knowledge Development Gap"			All			"Bureaucratic hurdles may delay curriculum reform efforts. Resistance from policymakers focused on other educational priorities. Limited awareness of the importance of soil science in education."	Conduct studies to analyse the impact of national curriculum review cycles on educational reform in soil science.	Research	Low	To be discussed
										Develop advocacy strategies to promote the timely integration of soil science into curricula.	Innovation		
										Collaborate with policymakers to streamline the curriculum review process.	Innovation		
NA	"More research is needed in assessing how high-quality and open-source materials can improve soil education and soil knowledge exchange."	C	"Knowledge Development Gap"			All			"Resistance from institutions to adopt non-traditional resources. Difficulty in ensuring the quality and relevance of open-source materials."	Create platforms for educators to share, adapt, and co-develop teaching resources and innovative approaches.	Innovation	Low	To be discussed
										Pilot Open-Source open-source soil health materials in diverse educational settings and evaluate knowledge retention.	Research		
NA	"More research is needed in evaluating and improving the effectiveness of distance learning for soil education, particularly for laboratory and field-based training."	C	"Knowledge Application Gap"			All			"Technical challenges related to online learning platforms may hinder program implementation."	Collaborate with educational institutions to pilot distance education options and evaluate their effectiveness.	Innovation	Low	To be discussed
										Develop evaluation frameworks for assessing distance education programs in soil science.	Research		
NA	"More research is needed in fostering skills and competencies in soil education that address real-world challenges."	B, C	"Innovation Knowledge Gap"			All				Conduct research on the competencies needed for effective soil stewardship and how to teach them.	Research	Medium	To be discussed

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