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Soils for SOLO Europe

Soil Mission Research & Innovation Roadmaps: significant updates and lessons learned

Deliverable D2.4

SUBJECT TO CHANGE

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Summary

Deliverable 2.4 aims at providing a second and updated synthesis of the Research and Innovation (R&I) Roadmaps being co-developed by the Soils for Europe (SOLO) Think Tanks (TTs) covering the first thirty months of the project. These actionable roadmaps address each of the Soil Mission Objectives (SMO) and are built under a transdisciplinary approach integrating the expertise of diverse type of stakeholders (e.g. scientists, farmers, industry and citizens among others) to identify soil-related research activities and priorities.

The information provided highlights the current state-of-the-art and identified knowledge gaps for each of the eight SMO, plus the topic of Nature Conservation of Soil Biodiversity. Hence, the content of this document is key for individuals involved in or interested in the transition towards healthy soils and those implementing or planning in conducting social-based research or projects integrating social science components. For instance, academic or research institutions, policymakers, private and public sectors, citizens, land managers, farmers, environmental organisations, among others.

Further essential sections are presented throughout this deliverable, for example, the methodological approach implemented to co-develop knowledge including the participatory activities and co-creation actions undertaken by each Think Tank (TT). These range from internal and thematic meetings within each TT to the input collected from stakeholders through participatory workshops conducted in the cross-fertilization events, held once per year.

During the cross-fertilization events, several activities intra and inter Think Tanks take place. These aim at discussing the work carried out by the Think Tanks in order to collect insight from diverse key stakeholders. The results are integrated into new versions of their scoping documents (from now on referred as “outlook”). After this, TT leaders conduct a series of meetings with their key stakeholders to discuss and co-develop the outlook. Then, the final documents undergo an open review process to reach a wider audience. This is what is defined in the project as the Soil Knowledge Network (SNK) materialised trough the ARPHA platform. Lastly, TTs leaders address the comments and suggestions gathered during the open review procedure after which, the final version of the outlook is finalised.

Therefore, the document contains pivotal information articulated as following:

- Current State-of-the-art of each topic related to the SMO, including the topic of Nature Conservation of Soil Biodiversity.
- Key knowledge gaps related to the SMO, plus the Nature Conservation of Soil Biodiversity.
- Actions and bottlenecks associated with the key knowledge gaps.
- Mid-term evaluation of the Think Tanks.
- Lessons learned and future steps regarding the performance of the Think Tanks.

In this regard, the results outlined throughout the deliverable are relevant for all diverse type of stakeholders, especially for those working on soil health related projects and/or initiatives as they present updated and detailed information in relation to each specific SMO. Furthermore, it is of equal importance to any individual or institution planning on establishing or evaluating working groups collaborating under a transdisciplinary approach such as TTs addressing a specific topic.

For policymakers especially, this document provides data based on a holistic perspective that could be useful for decision-making processes and as a resource to identify priority-areas across the EU in developing an agenda for funding research and innovation initiatives.

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List of abbreviations

ABC	Attitudes (Heart), Behaviours (Hands), Competencies (Head)
AWC	Available Water Capacity
BD	Bulk Density
C	Carbon
CA	Conservation Agriculture
CAP	EU Common Agricultural Policy
CBD	The Convention on Biological Diversity
CoE	Convergence of Evidence
CLC	CORINE Land Cover
CLIs	Community-led initatives
CLMS	Copernicus Land Monitoring Service
EEA	European Environmental Agency
EF	Ecological Footprint
EO	Earth Observation
ESD	Education for Sustainable Development
EU	European Union
ECF	European Competence Framework
EUSO	EU Soil Observatory
FAO	Food Agriculture Organization of the United Nations
FC	Field Capacity
FF	Food Footprint
FUA	Functional Urban Areas
GSP	The Global Soil Partnership
IMD	Imperviousness Density
IUCN	International Union for Conservation of Nature
JRC	Joint Research Centre
LD	Land Degradation
LDN	Land Degradation Neutrality
LfS	Learning for sustainability
LUC	Land Use Change

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MRIO	Multi-Regional Input-Output approach
NbS	Nature-based solutions
OECD	Organisation for Economic Co-operation and Development
PRTT	Soil Pollution and Remediation Think Tank
PTFs	Pedo-Transfer Functions
RA	Regenerative Agriculture
SMO	Soil Mission Objectives
SMS	Soil Management Strategies
SOC	Soil Organic Carbon
SOLO	Soils For Europe
SNK	Soil Network of Knowledge
SSM	Sustainable Soil Management
TCA	True Cost Accounting
TP	Total Porosity
TT	Think Tanks
TTL	Think Tank leaders
TTs	Think Tanks
UNCCD	United Nations Convention to Combat Desertification
UNEP	The United Nations Environmental Programme
UNSDGs	United Nations Sustainable Development Goals
WAD	World Atlas of Desertification
WRC	Water Retention Characteristics

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1 Introduction

This deliverable provides an updated synthesis of the *"outlook chapters"* and *"roadmaps"* co-developed by the TTs covering March 2024 to July 2025. The preparation of these documents undertook a series of co-creation actions involving the active participation of key stakeholder that are part of the Think Tanks. Nevertheless, it is key to highlight that each TT has not only integrated the inputs of their most close actors, but also the ones collected through an internal review process carried out among TTs. Additionally, an open review process was performed aiming to reach a wider public, leading to the expansion of the Soil Network of Knowledge (SNK).

The SNK is envisioned as a wide network of stakeholders drawing from soil scientist, soil ecologists, social scientists, economists, anthropologists, psychologists, educators, governance specialist, policy and lawmakers, farmers, landowners and their associations, NGOs, corporations to academic and research institutions. This network core is a community created with the intention of expanding beyond the project's scope.

This deliverable highlights the enhancements incorporated into the second set of documents prepared by each TT as a result of several interactive loops of discussions and refinements and corresponding to the period comprised from March 2024 July 2025. These include the result of the prioritisation exercise of the knowledge gaps identified per TT, that was conducted in the second cross-fertilisation event in Sofia, Bulgaria in November 2024. Moreover, all the inputs collected through the different participatory activities undertaken in this event are integrated into these documents. Finally, it includes the open review made in two rounds during 2025.

The outcome of the successive interactive loops, knowledge exchange and refinement produced 9 actionable roadmaps, one per each TT. The latter are being published as chapters in the Outlook for Soil Health 2025 which contains the knowledge gaps identified in each TT, the bottlenecks that have prevented filling these gaps, and the resulting required actions. This publication is a comprehensive, but also a living document that will be co-developed and updated with further input from the stakeholder community in future incoming versions.

This document is organized as follows: the first part includes an introduction and background of the project. Second, the evolution of the TTs is shown, including its state of the art and the description of the 3 knowledge gaps classified as the most important ones. Third, a midterm evaluation of the TTs is described incorporating major lessons learned from the outset of the project till date, and next steps envisioned for the incoming years.

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1.1 Project background

SOLO delivers actionable transdisciplinary roadmaps for soil-related research actions to increase soil health within the EU. To deliver those roadmaps, we focus on three pillars:

- Identification of the major knowledge gaps in research driving forces and bottlenecks through the 9 TTs.
- Assessments of synergies and trade-offs between TTs roadmaps and the regional nodes
- Co-development of an operational framework and a set of indicators to monitor the Soil Mission progress

Furthermore, it is essential to stress that while SOLO aims at developing these roadmaps addressing the diverse SMOs at the European level, there might be discrepancies in some regions in Europe regarding specific needs and priorities for research fundings. To tackle this matter, the regionalisation of roadmaps is made highlighting the main research and innovation

differences. Moreover, this is reinforced through the implementation of the Soil Weeks (designed and organised by all 12 SOLO partners) and Regional Nodes events emphasizing specific regions and land uses in Sweden, Portugal, The Netherlands and Hungary. Next efforts will entangle the interaction among regional and European scales.

To culminate in the overarching roadmap, first, an assessment of the priorities in relation to each SMO needs to be undertaken. For the purposes of SOLO, this is a key element. Therefore, the first attempt took place in November 2024 during the second cross-fertilisation event held in Bulgaria.

The prioritisation process was carried out in two parts. In the first part, key stakeholders cast the vote in the in-person event in Sofia. They were invited to select three of the top ten knowledge gaps identified by each TT (except for the EU footprints on soil, which only had top seven knowledge gaps) which culminated in a total of 27 votes for each actor. Circular stickers were provided to easily visualize votes after the exercise. Participants cast their votes simultaneously.

For SOLO, it is essential to ensure the active participation of most actors in the decision-making processes. Considering this, the second part focused on integrating the votes of key stakeholders that could not attend the in-person meeting. An online session was held aiming at replicating the procedure that was implemented in Sofia; hence, the same conditions and instructions were followed. Votes were collected through a Microsoft form that displayed the top ten knowledge gaps specific to each TT (seven for EU footprints on soils) and was configured in such manner that participants could only select three knowledge gaps. After this session, TT leaders received the results of the exercise to share with the participants.

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2 Soil Mission Think Tanks Evolution

The TTs are the core of SOLO and are conceptualised as knowledge-based groups ranging from a diverse variety of key stakeholders from different backgrounds, visions and areas of expertise working under a transdisciplinary approach to co-develop roadmaps for future soil research and innovation in Europe. The interaction focuses on two axes: i) interactions with several European entities and ii) continuous update of the main knowledge gaps identified, as well as drivers and bottlenecks. The SOLO TTs are also aspired to propose new avenues to face the R&I challenges for the next decade.

There are 9 TTs in SOLO, each is led by 2 institutions from the consortia integrating up to 30 members. During the first 18 months, the main focus was the population and launching of the TTs which required the implementation of several actions ranging from establishing internal governance model and the stakeholder engagement strategy. The latter included the initial screening process and mapping of stakeholders (prioritise and understanding their motivations and monitoring their engagement). Meanwhile, the first cross-fertilisation event was held in Barcelona which allow for more in-depth discussion regarding the identification of the knowledge gaps and the collaborative drafting of the first round of documents as well as the consolidation of the internal organisation of the TTs (D2.1; D2.2).

From that moment onwards, key activities and exercises were undertaken such as having a common understanding of main definitions incorporated in the roadmaps, the implementation of the first reflexive workshop involving TT leaders and a training session on facilitation and techniques to engage with stakeholders to:

- Enhance the content of the outlook chapters (previously named as scoping documents).
- Provide guidance regarding stakeholder engagement actions, co-creation activities e.g. ensuring an open dialogue to promote knowledge exchange, fostering collaboration for the co-production of the project outputs.
- Identify strategies to integrate both the driver's analysis (WP3) and the information of the TT's roadmaps be synthesised in the overarching roadmap (WP4).

The first round of activities led to D2.3 results, where the first discussions and drafts took place (including all the findings and discussions since the outset to February 2024). From then onwards, a second round of feedback was undertaken per TT (throughout the whole year and being the Wageningen workshop a milestone in April 2024), among the TTs (in Bulgaria November 2024), among the WPs (especially in the consortium meeting in Lund May 2025) and the open review made in ARPHA per each TT results (including the state of the art and prioritized knowledge GAPs; June 2025).

Then, the latest feedback presented below integrates the current versions of the outlook chapters including the insights collected during the internal review process among TTs (from March 2024 till June 2024), the second cross-fertilisation event (November 2024), and the two rounds of the open review process in ARPHA.

The main components of the outlook chapters for the 9 TTs are presented below: the current state-of-the-art addressing SMOs and the topic of Nature Conservation of Soil Biodiversity. In addition, the description of the top three knowledge gaps identified per each TT is highlighted. It is worth mentioning that the content of these documents also includes the insights of multiple stakeholders of each TT collected through a series of participatory dynamics (in-person and online).

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2.1 Reduce desertification

2.1.1 State of the Art

Land degradation has emerged as a critical global issue, undermining food security, ecosystem services, and long-term land productivity. In response, international institutions have sought to establish common definitions and coordinated actions. 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. Simultaneously, the United Nations Convention to Combat Desertification (UNCCD) has framed Land Degradation Neutrality (LDN) as a central goal of its 2030 agenda (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.

Within this policy landscape, land degradation is increasingly recognized as a "wicked problem"—a complex, systemic challenge that intertwines environmental processes with socio-economic and governance dimensions (Fig 1).

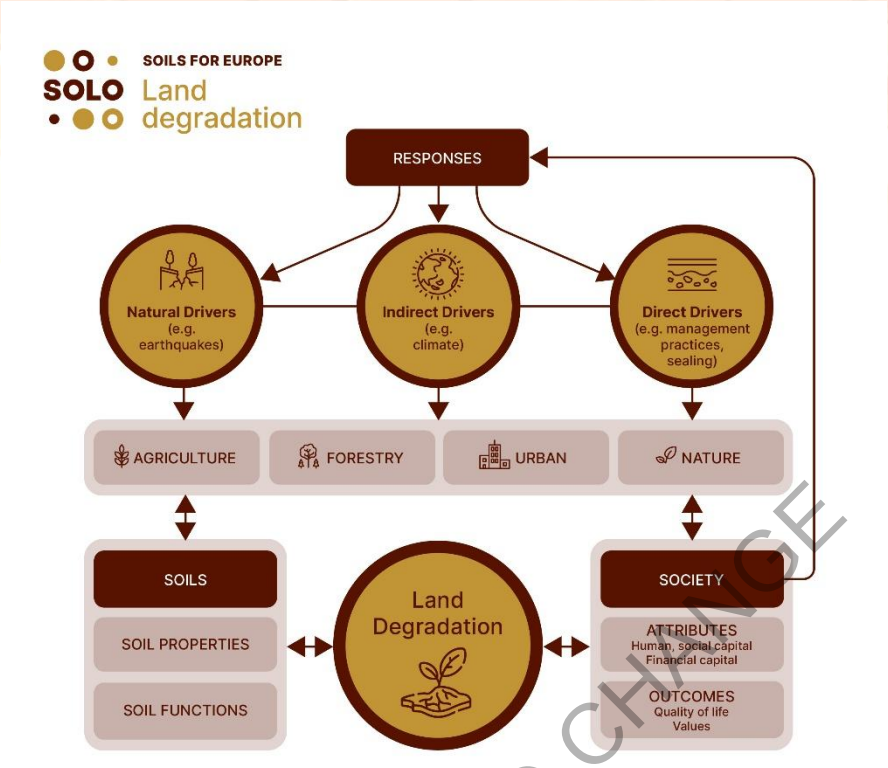

Figure 1: Land Degradation: A transdisciplinary challenge

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Land Degradation poses significant challenges. Therefore, in recent decades, several 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, such as Soil Organic Carbon Dataset, and the Salt Affected Soils Dataset of the FAO. The FAO also provides a plethora of relevant complementary datasets, such as the Global Salinization map.

More recently, the EU Soil Observatory (EUSO) has emerged as a pivotal platform for centralizing and visualizing soil-related information at the European scale. Through the EUSO Dashboard, datasets covering erosion (e.g., RUSLE and RWEQ-based models), contamination (e.g., copper and mercury excess), and nutrient imbalances (e.g., phosphorus deficiency/excess) are now accessible for researchers and policymakers alike. However, while these datasets are invaluable, methodological inconsistencies, differences in spatial resolution, and the lack of socio-economic overlays limit their standalone utility for integrated degradation assessment.

In terms of concepts and methodologies, 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. This conceptual framework has been widely 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).

Similarly, another 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* 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 national level, 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. 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 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).

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 (MQI) and the Social Quality Index (SoQI) were integrated under several climate change scenarios (Perović et al. 2021, Prăvălie et al. 2020).

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, a clear and consistent framework for soil degradation assessment 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.

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Considering the above, it can be concluded that there have been significant advancements. 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.

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 unravelling 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).

2.1.2 Prioritised knowledge gaps

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:

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<u>Addressing Trade-offs in Restoration: Insights from Grassland Studies</u>

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, 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 semiarid 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 pedoclimatic 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:

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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, remain 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).

Besides, 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 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,

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which, as the literature 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 TEERinitiative (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.

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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 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 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.

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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 Commission 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 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.

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2.2 Conserve and increase soil organic carbon stocks

2.2.1 State of the Art

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 commission 2023b), however gaps remain due to limited data on various soil degradation issues. Soil health is closely linked to SOC, as soil organic matter affects soil structure, soil life and elemental cycles, which together sustain essential ecosystem functions such as erosion protection, soil 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 commission 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

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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:

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

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2.2.2 Prioritised knowledge gaps

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 is 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.

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 fibre 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 fibre 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 (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 produces 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).

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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 weeding 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) indicate, though, that unless appropriate farming practices are implemented, expanding organic farming might reduce the potential for soil carbon sequestration. According to Lorenz et al. (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 consist of a range of different practices that vary varies 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) 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 (Francaviglia et al. 2019).

Forest management must incorporate adaptive strategies to address climate change impacts, such as altering tree species composition, adjusting rotation periods, and modifying stand

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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 deeper 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.

(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 existing research to practical applications remains insufficient (iii) assess these effects, research on harmonising measuring, accounting, monitoring and model development across Europe is required.

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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 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).

Soil biodiversity plays a critical role 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), while 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 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 in which 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

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(Tilman and Downing 1994). It may be the case that in a grassland clay rich soils where essential nutrients are limiting 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, 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 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

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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 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 below ground 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

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(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.

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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, nonproductive 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 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 (N2O) 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.

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2.3 Reduce soil sealing and increase the reuse of urban soil

2.3.1 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.

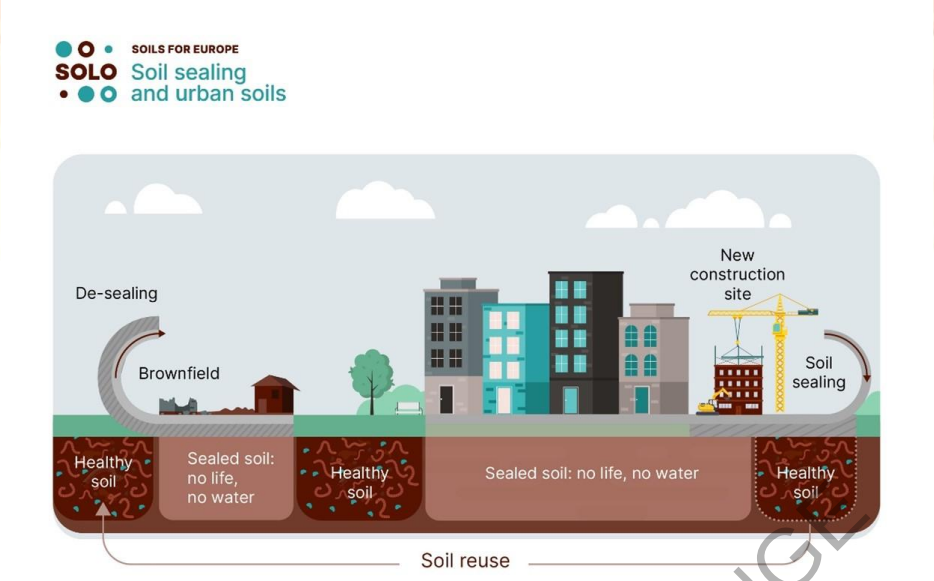

Figure 2: Illustration of the Think Tank topics and their relationship

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Despite being among the human activities with the greatest impacts on soil, data on sealing at the European level was 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 10m resolution of the newer maps (starting 2018) disrupted the consistency of the temporal series. 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*). Grey recycling, i.e., the internal conversions between residential and/or nonresidential land cover types, was secondary 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.

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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 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 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 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).

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2.3.2 Prioritised knowledge gaps

Knowledge gap 1: 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 incentive-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 considering the local context, thereby undermining its 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

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ambitious no-net targets, a single instrument is insufficient, and a policy 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?

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Knowledge gap 2 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 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 exacerbates 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?

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Knowledge gap 3: 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.

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, emphasizing 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 standardized 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). Costbenefit 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)?

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3. How to identify and prioritise suitable areas for desealing interventions based on their environmental and social impact?

Knowledge gap 3: 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: 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 enhance 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’

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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 emphasize 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?

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2.4 Soil pollution and restoration

2.4.1 State of the Art

Agriculture Organization of the United Nations (FAO), the United Nations Environment Programme (UNEP) and 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. While the differences can be justified, it makes comparative analysis difficult, especially when data mining tools are used.

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, while further elaborating and optimising the system-approach based on the literature listed in the reference list and feedback from our stakeholders. The following studies provided, among others, 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).

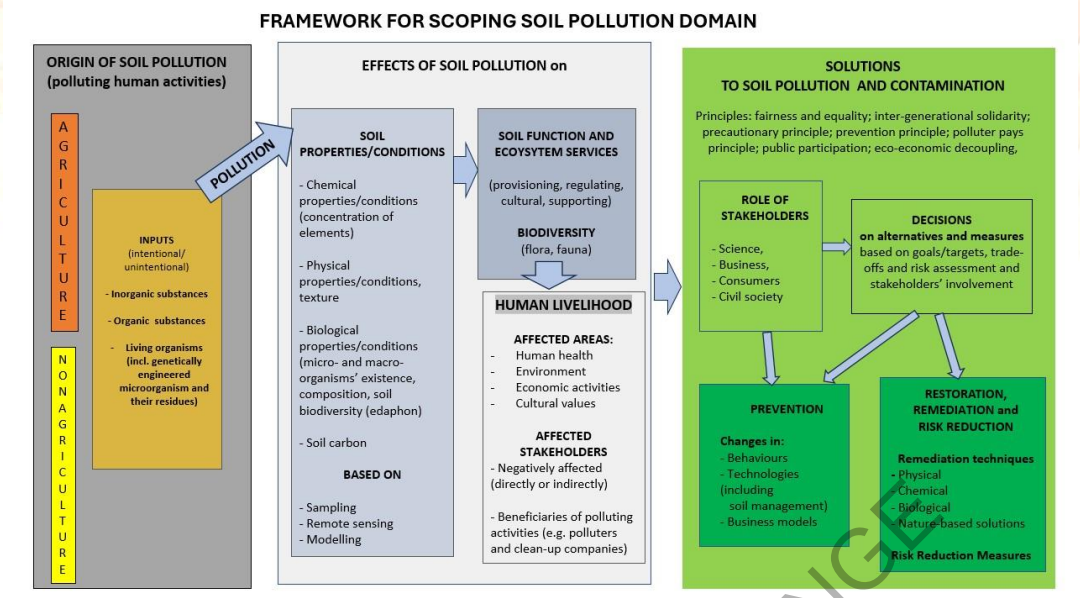

Figure 3: Refined concept overview of System approach to identify interlinkages between domains related to soil pollution/contamination (created by the PRTT).

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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. The development of the framework was driven by the Soil Mission Objectives relevant to the Soil Polluttion and Restoration Think Tank (PRTT) which focus strongly on pollution from agricultural activities and sets specific targets related to agriculture (pesticides, fertilizer use, nutrient losses, organic farming) and microplastics, 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, pollution originating from intentional or unintentional introduction of potential pollutants including (i) inorganic substances, (ii) organic substances, (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.

Impact of soil pollution on biodiversity, ecosystems and stakeholders

Although, the extensive negative (potential) impacts of different soil pollutants on biodiversity and ecosystem functioning have been shown by a variety of studies, the full, long-term impact ofthe cumulative effects of different soil pollutants or the interactive effects of these different groups of pollutants, being present concurrently in soils (e.g. plastics, pesticides, metals, ...), 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 functions.

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Different studies have indicated that soil pollution directly affects human health. Soil pollution can contaminate food, which can pose risks for human health. Pathways other than ingestion or food, such as inhalation or skin contact, are not or not adequately assessed. Soil pollutants, such as pesticide residues, can accumulate in the lighter top layer of the soil, get transported by the wind and inhaled by animals and humans.
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.

Sources and scope of soil pollution
In this section, a first overview is given of important factors contributing to soil pollution. 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 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.

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.

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).

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

Current legislation and funding do 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).

2.4.2 Prioritised knowledge gaps

Knowledge gap 1: Impact of soil pollutants (individual and mixtures, short-term and long term) on soils and soil ecosystem services

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 gaps exist 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).

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.

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Knowledge gap 2: Socio-economic and market tools to prevent soil pollution and their fitness-for-purpose

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

Actions

- 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,
- 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 (True Cost Accounting) 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) relationship 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.

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Knowledge gap 3: Impact of soil pollutants (individual and mixtures, short-term and long-term) on human Health

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.

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 biodiversity, ecosystem functions and 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.

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2.5 Soil Erosion

2.5.1 State of the Art

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 yr , based on soil formation rates (Verheijen et al. 2009). Soil erosion primarily acts on the topsoil and can range from sheet and rill erosion to gully erosion, which extends into deeper soil layers. It can also impact the subsurface through processes such as piping and/or lateral subsurface erosion. Soil erosion removes the most valuable fraction of the soil (i.e., organic horizon), which typically contains the highest content of organic matter and nutrients, the most intensive soil life, and possesses the highest capacity to support life (Poesen 2018; Koch et al. 2013; Eekhout and de Vente 2022). Therefore, the impact of soil erosion is not only the quantity of removed soil mass, but also the loss of associated soil functions (Lal 2010). Moreover, soil loss can have relevant repercussions in agroecosystems (food and timber production, water regulation, carbon sequestration, nutrient cycling and biodiversity), highlighting the need to increase the inputs to effectively manage agricultural and forestry production (Milazzo et al. 2023). Soil erosion may increase the on-site desertification risk through two mechanisms: by reducing soil water retention capacity and by reducing soil fertility, which is driven by soil organic carbon losses (González-Pelayo et al. 2024). This diminishes both evapotranspiration and temperature regulation capabilities. Furthermore, eroded soils lose their ability to support life, thus amplifying air temperature increases and indirectly exacerbating climate change. Soil erosion can also create deep and fertile soils in deltas and fluvial terraces under natural or geological soil erosion rates. However, an accelerated soil erosion rate can contribute to the degradation of the soils developed in lowlands as a consequence of the excessive sedimentation. This watershed and basin scale process can be found also at field and slope scale when soil erosion is accelerated as a consequence of tillage such as the increase in connectivity of sediments and water (Rodrigo Comino et al. 2018).

Soil erosion also accounts for multiple off-site effects (Panagos et al. 2024b), such as increasing sediment, nutrient and pollutant concentrations in water, therefore hindering aquatic life, water quality, or reducing water storage capacity, and increasing water treatment expenditures, as well as the risk of flooding and debris flow during high rainfall and runoff events. It is estimated that sediment accumulation, resulting from soil erosion in the EU's large reservoirs (approximately 5000 in total) exceeds 1 billion m, with an anticipated cost of ranging from 5 to 8 billion € annually (Panagos et al. 2024a). Fig. 4 exemplifies soil erosion effects.

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Figure 4: Social, economic and environmental impacts of soil erosion

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The monitoring of soil erosion and its impacts are among the greatest challenges involving erosion studies (Huber et al. 2009). Besides field monitoring, there is a wide variety of soil erosion models (Batista et al. 2019; Karydas et al. 2015; Zdruli et al. 2016) making use of diverse spatio-temporal scales (Borrelli et al. 2021). In essence, both past and recent model applications provide estimates of susceptibility to soil erosion for natural landscapes, forests and croplands, spanning from the global scale down to the plot scale, and even incorporating projected climate change scenarios (Borrelli et al. 2023; Borrelli et al. 2022; Vieira et al. 2025). Such a top-down approach, based on consistent methodology, can be very informative. Up to date, the dominant focus in erosion modelling lies on water-induced erosion, accounting for approximately 95% of the studies. Conversely, modelling on wind erosion, tillage and co-extraction on root crops and land-based machinery remains relatively limited (Borrelli et al. 2021). While modeling efforts have advanced, it is important to recognize that models have limitations (Schmaltz and Johannsen 2024), and thus, measured empirical data is essential, as models need validation (Batista et al. 2019) and cannot integrate the complexity of interactions governing all the erosion processes, particularly the multi-process modelling approach. Field monitoring capturing high-resolution datasets and conducting thorough long-term periods have been essential to enable models to achieve better calibrations, as well as facilitate effective validations (Alexiou et al. 2023). Moreover, for field studies to be considered suitable in modelling, they must rely on accessible and comparable methodologies. Initiatives such as the EUSEDcollab database (Matthews et al. 2023) may represent a paradigm shift, providing open-access and harmonized catchment data from various European countries, particularly relevant for soil erosion modelling. While such initiatives are scarce, they represent a significant endeavour 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, the TT has necessarily adopted an interdisciplinary and systems thinking approach to address the issue at hand. From this effort, a total of 24 knowledge gaps were identified. The following section will address the top 3 knowledge gaps identified through a prioritization exercise conducted over the past few months by SOLO partners and participants in the TT.

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2.5.2 Prioritised knowledge gaps

Knowledge gap 1: There is a need to co-construct soil erosion prevention techniques and fields 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 frontrunners, 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 owing 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 codeveloping effective prevention techniques tailored to local conditions. Similarly, Lima et al. (2017) underline the value of iterative design and practical application in soil erosion prevention, emphasizing the need for co-construction with practitioners to ensure strategies are workable, effective, and context specific. The ongoing demand for data validation (Polyakov et al. 2023) further highlights the critical role of practitioners in ensuring that soil erosion prevention measures are grounded in the complexities of real-world applications. However, such data remains scarce and difficult to obtain (Wang et al. 2024), not least because of the time and resources needed for key actors to participate and contribute with data and often requires a stepwise approach to ensure systematic collection and integration. While we can suggest conservative and regenerative measures, without dedicated demonstration sites and financial support for practitioners, acceptance may remain limited. To address this issue, Soil Mission Lighthouses serve as an important interface and demonstration platform, showcasing the best management practices to prevent soil erosion under local conditions. This fosters knowledge exchange between scientists, policymakers, and land users, building trust and encouraging the adoption of innovative soil protection measures. Furthermore, productivity and financial support guarantees are essential for farmers, foresters, and other land managers to take the risk of implementing alternative measures instead of conventional ones. Within the framework of Soil Mission Lighthouses and their inherently transdisciplinary nature, establishing a strong governance structure is essential. This requires partnerships that include not only researchers and practitioners but also implementation and integration experts who are responsible for ensuring integration and overseeing the process (Hoffmann et al. 2022).

Lastly, data scarcity and the recurring arguments justifying information gaps are not new. Initiatives such as EUSEDcollab, an open-access database which compiles data on runoff, soil loss by water erosion and sediment delivery (Matthews et al. 2023), are positive and should be continually supported, but gaps in data representativeness persist, leading to datasets that do not adequately represent the wide range of geographical, environmental, and land management contexts where soil erosion occurs. Overcoming these issues requires testing new measurement approaches through the integration of remote sensing-based innovation and technology that

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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.

Knowledge gap 2: There is need to co-develop tools that can support managers' and landowners' decision making

While monitoring systems and modelling tools play a pivotal role in supporting and enhancing decision-making processes, it is equally essential to engage with managers and landowners while co-developing tools that can support (or influence) their decision making. Understanding their motivations during land management is critical, and collaborative approaches and governance mechanisms need to be developed jointly (Panagos et al. 2020a; Briassoulis 2011). For instance, Debeljak et al. (2019) designed a decision support system to assist land managers in assessing and improving soil functions, demonstrating how such tools can be co-developed to align with practical needs. Similarly, Terribile et al. (2024) highlights how co-designed decision support systems can empower stakeholders to protect soils and land, emphasizing the role of innovative tools in facilitating decision-making for erosion prevention. Borrelli et al. (2023) showed the importance of tools that integrate complex datasets to support managers in mitigating soil erosion risks effectively, whereas a multi-model approach had a critical role in identifying erosion hotspots globally, thus providing significant data for policymakers and land managers. Stankovics et al. (2024) demonstrated the LANDSUPPORT project which developed a geospatial Decision Support System (DSS) through a collaborative approach with policy stakeholders. This system integrates data across multiple scales — local, regional, national, and European Union levels — to assist in sustainable land management and soil protection. The co-design process involved extensive user engagement, including semi-structured interviews and questionnaires, ensuring the DSS met the practical needs of its users. In line with this, the EU SoilCare project developed an interactive mapping tool that spatially visualises where in Europe soil-improving cropping systems (SICS) can be most effectively applied (SoilCare 2025). Additionally, the ongoing TERRASAFE project (2024–2029) is building tools to map desertification hotspots in Southern Europe and North Africa through a multi-actor, codesigned approach with local communities (TERRASAFE 2025).

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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).

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Knowledge gap 3: Representation of ecosystem services' losses following soil erosion

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

However, a broader representation of these losses - both on- and off-site - is missing, hindering a complete understanding of the environmental impacts of erosion. It is imperative to quantitatively, as well as qualitatively, represent the losses of ecosystem services following soil erosion and concurrently occurring soil degradation processes (Krull et al. 2004; Keesstra et al. 2018a; Jacob et al. 2021). The links between soil erosion and the resulting declines in agroecosystem conditions remain poorly understood. In particular, erosion-induced losses and their direct consequences, such as the diminished ability of ecosystems to provide essential services like crop production and water regulation, should be effectively quantified and integrated into sustainability frameworks (Rendon et al. 2020; Steinhoff-Knopp et al. 2021). Establishing and quantifying the relationships between soil erosion and other ecosystem services will allow the optimization of soil management solutions that contribute to maximize positive effects at the lowest cost.

Moreover, quantifying and, particularly, valuing the effects of soil erosion on other ecosystem services is of paramount importance, as it makes the assessment of the benefits more comprehensive and effective, and increases the ability to measure and implement synergies between human activities and soil ecosystem services (Fernandes et al. 2019; Petratou et al. 2023). For example, Pires-Marques et al. (2021) estimated the avoided costs of soil erosion in a mountainous region of northern Portugal at €1,144/ha/year using an indirect market valuation

method. To implement effective trade-off mechanisms in planning and management, it is crucial not only to consider formal objectives but also to develop a functional contractual system and fair incentive mechanisms. These incentives must be attractive enough to discourage unsustainable land use (Fernandes et al. 2019), such as payments for ecosystem services, market-driven instruments, habitat banking, biodiversity offsetting, Tax Increment Financing, tax incentives, and subsidies. Learning from CAP implementation, it is also important that incentive requirements are ambitious (both at EU and Member State level), and that, in complex incentive schemes, assessing the results of measures that specifically address sustainable soil management is promoted (European Court of Auditors 2023).

2.6 Soil Structure

2.6.1 State of the Art

Soil structure dictates the hydraulic properties of soil and is dependent on the soil properties such as organic matter content, texture, bulk density, stoniness and porosity (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 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).

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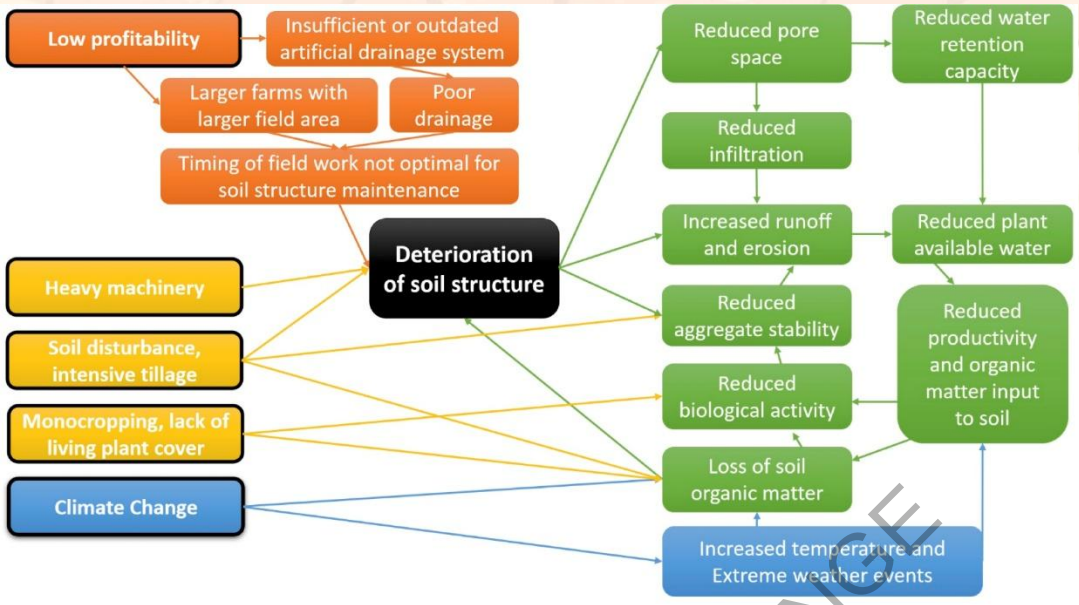

Figure 5: Drivers (black borders) affecting structure of agricultural soils include factors such as overall policies and economic situation (orange), soil management practices (yellow), and environmental factors (blue). Structural deterioration can impair soil functioning and create a vicious cycle of further soil weakening

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Intensification of land management 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 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 are 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 in 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 soil 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 organisms 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. 5) we can also preserve 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?

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2.6.2 Prioritised knowledge gaps

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 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 may differ depending on climate, soil type and 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 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 the provision of as many ecosystem services as possible.

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 allowing the 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 also concern particulate material (suspended solids) as well as nutrients essential for 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. Consequently, it is essential to develop management strategies that account for both extreme rainfalls 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 destabilizing effect can be reduced. For example, soil wetness and inherent soil properties contribute to soil structural vulnerability, and their interaction is complex depending also on the management practices (Hu et al. 2023). 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). 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 and site preparations. If continuous cover forestry practices get more common 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

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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.

Knowledge gap 2: How can we quantify and value soil structure to support sustainable land management, economic assessments, and predictive modelling across scales and applications?

A good soil structure is characterized 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 by at 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 expected to be produced by the soil within the land use and the capacity of the specific soil type.

Soil aggregates are considered hot spots for biological activity and biogeochemical processes. They 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. In fact, tillage produced aggregates are often loosely packed and form inter-fragment spaces whereas natural aggregates are more likely to be seamlessly embedded 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

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importance of understanding aggregation and developing methods to study aggregates in their functional surroundings.

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 kinds of soils. Some methods are cheap and widely applicable in context with the field sampling and utilized for example in the current European-wide field studies and surveys, but less informative and difficult to be interpreted. For example, soil bulk density is a widely measured property used to describe soil structure. However, interpreting bulk density (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 such as pore connectivity. On the other hand, certain newer methods, such as X-ray computed tomography (CT), allow 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 rely on rare equipment.

Further, soil structure contributes to ecosystem services in different scales (micron, pedon, catchment). 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, satisfying 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 the 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. The 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.

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Knowledge 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?

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 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 soils ability to stand erosive forces. Soil aggregates are associates of organomineral particles bound together with forces that are stronger than the forces between adjacent soil aggregates; biologically synthetized extracellular polymeric substances (EPS). EPS are composed mainly of polysaccharides, proteins and DNA excreted by soil microorganisms. Extracellular 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 stabilize 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 via microbial activity, 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). They may also mitigate soil compaction damages (Jin et al. 2017). Abundant use of fertilizers decreases the benefit of root–soil interface in nutrient uptake, and modern crop cultivars may have smaller root systems. These may lead to lowered amounts of rhizodeposition

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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 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?

The 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, the recovery of vast areas of deteriorated soils on Earth is a challenge.

SUBJECT TO CHANGE

2.7 Reduce the EU global footprint on soils

2.7.1 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 EU level, assessing the overall status of soil health remains a significant challenge. At 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 continued.

While 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 brought together a summary of recent efforts. We also identified key databases that offer the potential for assessing EU global soil footprint. We emphasize that this document focuses on the footprint of food, fiber and biomass production, as this is the specific focus of SO7. This does not imply that no other footprints are worthwhile to investigate, as also highlighted by multiple members of our SOLO Think Tank.

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 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.

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 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 bioeconomy. They linked the biophysical model LANDFLOW with the EXIOBASE 3 MRIO model, to provide detailed insights into product and country-specific footprint. This paper provided the first assessment of the global cropland footprint of non-food products of the European Union (EU). 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.

SUBJECT TO CHANGE

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, 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. Key findings revealed that a significant share of Sweden's pesticide footprint is embedded in imports, primarily from Europe and Latin America.
- 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. 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.

Habitat loss and agricultural trade

Schwarzmueller and Kastner (2022) performed a study that linked agricultural trade to global loss of species. 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.

In another study linking biodiversity decline to agricultural expansion, Zabel et al. (2019) predicted global impacts of future cropland expansion and intensification on biodiversity. 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.

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.

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).

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:

- ISRIC
- The Global Soil Partnership (GSP), established by the Food and Agriculture Organization (FAO)
- The Global Footprint Network

SUBJECT TO CHANGE

Based on the state-of-the-art, it becomes clear why Mission Objective 7's first subobjective is focused on setting a clear baseline for establishing the EU's global soil footprint in line with international standards.

2.7.2 Prioritised knowledge gaps

Knowledge gap 1: 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.

SUBJECT TO CHANGE

Knowledge gap 2: 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?

Knowledge gap 3: Trade-offs between 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 prioritisation should not select one perspective and discard the others.

2.8 Soil literacy

2.8.1 State of the Art

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.

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).

The lack of soil is not limited to citizens, youth, students or farmers, but also extends 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).

SUBJECT TO CHANGE

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 study is supported by The ABC of Soil Literacy Report from the University of Durham (Johnson et al. 2020) which 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 6).* The idea of hands, head and heart is ideated by the TT.

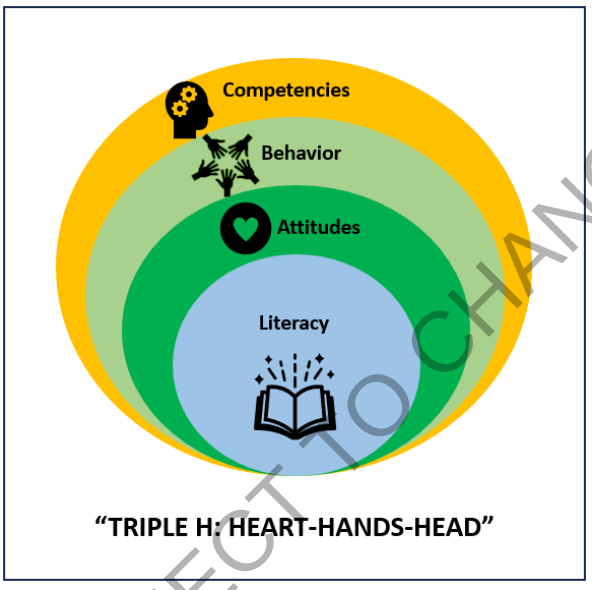

Figure 6: Components of soil literacy emphasizing the ABC (Attitudes, Behavior, Competencies; (Johnson et al. 2020)). Heart in relation to feelings-values, Hands in relation to action management and Head in relation to abilities-capacities

SUBJECT TO CHANGE

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.

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.

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. 7).

Figure 7: Awareness-to-action continuum for soil health

SUBJECT TO CHANGE

2.8.2 Prioritised knowledge gaps

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.

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 sensitizing of all the senses. This emphasizes 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, “Recognizing 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 emphasize 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 educational frameworks to teach sustainability concepts across diverse educational settings?

SUBJECT TO CHANGE

Knowledge gap 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 campaigns.

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?

SUBJECT TO CHANGE

Knowledge 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.

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 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?

SUBJECT TO CHANGE

2.9 Nature conservation of soil biodiversity

2.9.1 State of the Art

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).

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 yet (Phillips et al. 2020).

Thorough assessments of the contributions of soil organisms to ecosystem services are urgently needed to guide decisions regarding trade-offs in choosing areas to conserve and conservation methods. Fig. 8 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.

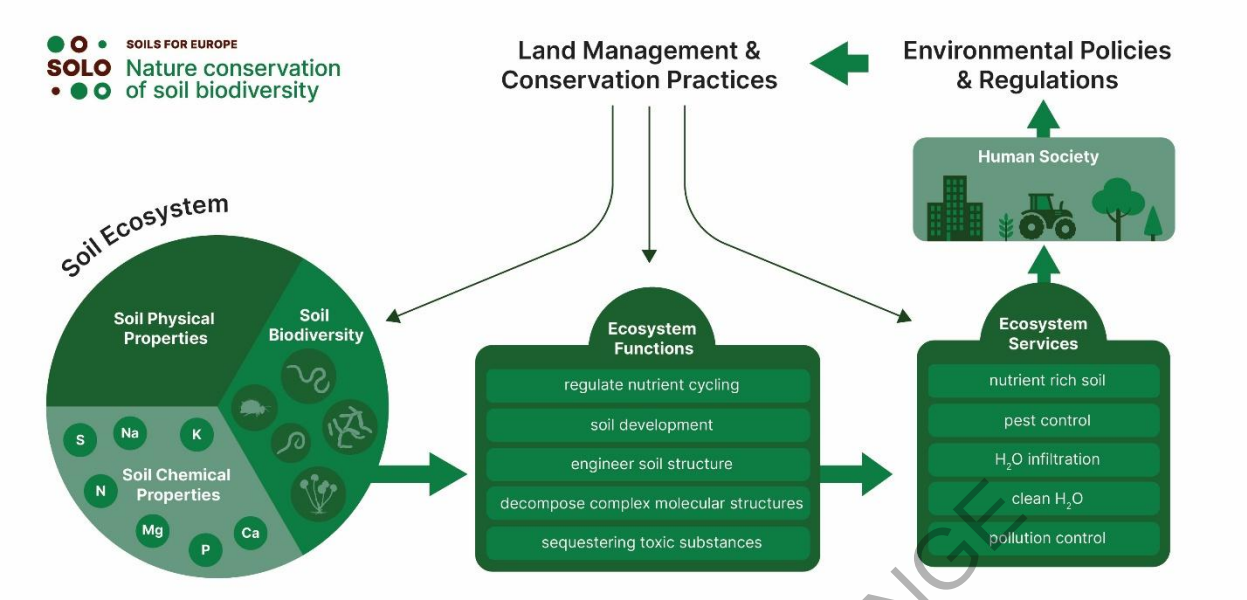

Figure 8: Soil biodiversity is integral to ecosystem functions and benefits human society through its associated ecosystem services. In turn, conservation and land-management policy and decision making directly impact soils biodiversity and, indirectly, ecosystem functions and services

SUBJECT TO CHANGE

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. 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.

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

Integration of conservation into sustainable use

Protected areas have long been the most important tools in biodiversity conservation. However, 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.

The EU Common Agricultural Policy (CAP) provides several suggestions on how to protect soil biodiversity through soil health. However, discussions and data concerning soils and their 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).

SUBJECT TO CHANGE

Soil biodiversity conservation

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). 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 2011 – 2022 that consider conservation of soil and soil biodiversity (Guerra et al. 2021b). 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).

Soil biodiversity conservation awareness and information sharing

At regional and local levels, awareness-raising efforts targeted at stakeholders, the general public and in education are needed to gain support for and co-develop policies for soil biodiversity conservation with the public, industry, and other stakeholders in both regional and EU-wide contexts.

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), which 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.

2.9.2 Prioritised knowledge gaps

Knowledge gap 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 standardization 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 standardized 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 functions 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 standardization 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 standardization has been further supported by significant initiatives such as the Earth Microbiome Project (earthmicrobiome) which already suggested standardized protocols more than a decade ago. This knowledge is key to providing standardized 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.

Table 2 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

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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.

Table 2: 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 1: soil respiration Tier 2: Bacterial and fungal	European-scale monitoring	Römbke et al. 2006, Bispo et al. 2009

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Tier 2: Macrofauna; Mites; Nematode functional diversity; Bacterial and fungal diversity by DNA or PLFA	activity		
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

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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
    - Methods 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 standardization and comparison across databases

- 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).

Knowledge gap 2: The valuation of soil biodiversity

The value of soil biodiversity and ecosystem services to environmental and human wellbeing 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 Total 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).

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 multiple 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

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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 an issue with this is that this method lacks an agent for the valuation and only compares values of goods, e.g. food production (Pimentel et al. 1997, Jónsson and Davíðsdóttir 2016, van der Putten et al. 2012). These authors suggest that maintaining a diversity of functions to sustain ecosystem services may be more important than the presence of certain species, *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 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 to climatic gradients, soil organismal ecologies, and the change in weather and climatic condition (Scherzinger et al. 2024).

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Knowledge gap 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), 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. (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

<u>Actions to fill gaps in soil biodiversity conservation and restoration methods:</u>

- Explore and promote land management strategies improving soil biodiversity.

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- Evaluate current and future policy instruments and develop decision framework 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.

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3 Midterm evaluation of the Think Tanks

The midterm evaluation of the Think Tanks represents a pivotal milestone within the project. It outlines the opportunity to discuss collectively the activities undertaken during the first 30 months of SOLO. The aim is to reflect on the TTs performance taking into consideration the main drawbacks and successful actions to determine measures to improve the outputs of the TTs in the following phase of the project.

In the framework of WP2 several reflexive dynamics have been carried out with both key stakeholders and TT leaders. Furthermore, a key aspect of the evaluation is to highlight the main lessons learned in the process, especially when working under a participatory and transdisciplinary approach, which are crucial elements of SOLO. Table 3 chronologically summarises all the reflexive dynamics undertaken till date.

Table 3: Compilation of reflexive dynamics undertaken in SOLO

REFLEXIVE DYNAMICS IN SOLO				
Name of the dynamic	**Aim to**	**Objective**	**Format**	**Outreach**
Open-ended survey for TT leaders	TT leaders	Collect feedback from TT leaders in relation to key elements of the project (in-person meetings, ARPHA, internal organisation, WP2 functioning, etc). This was the baseline for the reflexive activities conducted in Wageningen.	Online survey	Internal
Peer-led coaching session	SOLO partners, concretely to TT leaders	Promotes mutual learning and it seeks to facilitate mutual understanding and collaborative resolution of shared challenges. At the end, participants find a new and helpful way of addressing an issue	In-person during the 18M Consortium meeting	Internal
Sailboat retrospective	SOLO partners, concretely to TT leaders	Through this method, SOLO project partners and TT leaders were able to identify what went right, what went wrong and what improvements and changes can be introduced in the future	In-person during the 18M Consortium meeting	Internal
Open-ended survey for key stakeholders	Key stakeholders	Collect feedback from only key stakeholders in relation to key aspects of the project (cross-fertlisation events, knowledge exchange actions, communication efforts, engagement strategies, etc).	Online survey	External
Story mapping	TT leaders based on the feedback collected from key stakeholders through the survey	Method selected to conduct the midterm evaluation of the TTs. All the actions detailed above served as baseline to design the workshop in which the evaluation finalised.	In-person activity during the 30M consortium meeting	Internal

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In the following subsection the methodology compiled in the Table 3 is described including both the work carried out internally by the TTL, and the one made by the TTs with their stakeholders (3.1). Next subsection the overall lessons learned from both processes are summarized (3.2).

3.1 Methodology for the TTs reflexive process

The initial seed of these activities was the preparation of a survey aimed at collecting feedback from the TT leaders. This survey included crucial sections in relation to the development of the project to detect areas for improvement, for example, the launching of the TTs, stakeholder engagement, the roadmapping process, the first cross-fertilisation event, the first round of the open review process through ARPHA, overall functioning of WP2, D2.1; D2.2 and the SOLO platform. Furthermore, open-ended questions were incorporated to enable TT leaders to articulate their perspectives more freely.

All feedback collected through the survey constituted a central pillar for the conceptualization and execution of the reflexive dynamics undertaken at the consortium meeting in Wageningen. Then, during the M18 meeting held in April 2024, two sessions were undertaken. The first one named *"Peer-leading coaching session"*. This dynamic aims at enhancing the interactions of the participants, in this case, the TT leaders to helping each other understanding and collectively solve common challenges. An essential aspect is that all participants engage in mutual learning through a horizontal and collaborative approach fostering an open dialogue. To conduct this activity, participants were divided into two groups. The first group was led by the soil literacy TT leader and the latter by the soil structure TT leader. Figures 9 and 10 underscore the principal findings for both groups:

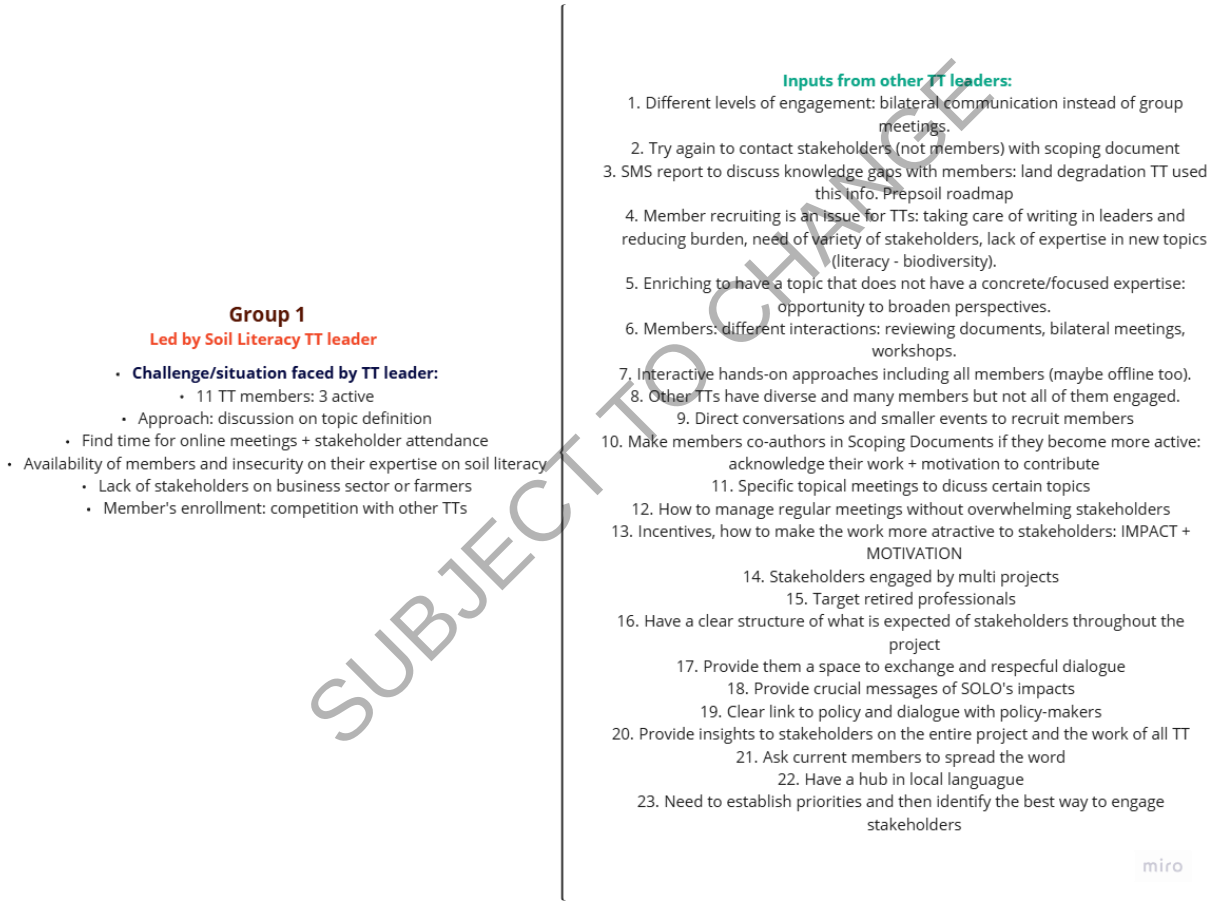

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Figure 9: Peer-led coaching session results – group 1

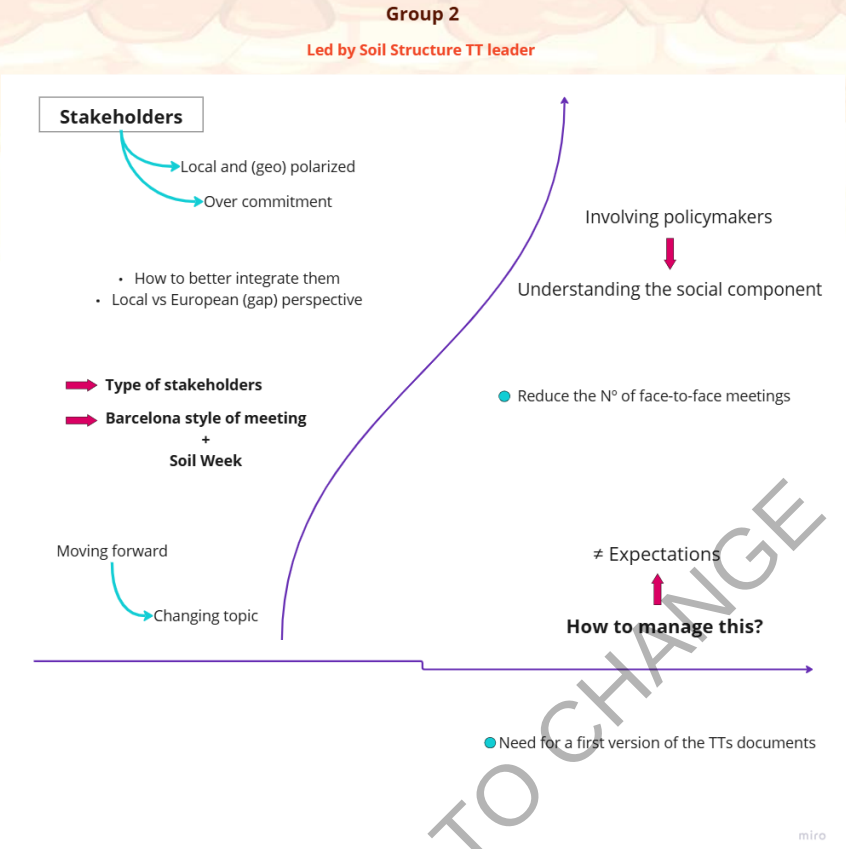

Figure 10: Peer-led coaching session results – group 2

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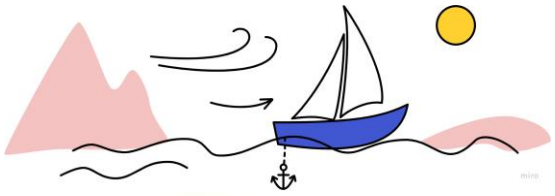
Then, on the last day of the consortium meeting, the last reflexive and participatory dynamic was undertaken. The Sailboat technique for retrospective is an interactive and low-key way to reflect on the project. Through this method, participants can identify what went well, what went wrong and what improvements and changes can be introduced in the future. Table 4 highlights the main insights collected through this activity.

Table 4: Sailboat retrospective main findings



What helped us move forward?	What made us feel good?
○ Aim of the project ○ Cooperation ○ Periodic meetings with stakeholders ○ Feedback	○ Support from partners ○ Exchange of ideas ○ Good feedback ○ Responsive colleagues

○ Engagement and motivated stakeholders ○ Informative meetings ○ Communication ○ Reviews ○ Different expertise ○ Pensoft ○ Project meeting twice a year ○ After first outlook, scenarios of different paths ○ WP2 monthly meetings ○ Barcelona meeting ○ Soil weeks ○ Regular internal comments ○ Outlook template ○ Prioritization method ○ Best practices (TT) ○ Combine soil weeks with other events	○ Encouragement from other TT members ○ SOLO meetings ○ Meaningful discussions ○ Motivation ○ Project meeting twice a year ○ Collaboration among TTs ○ Stakeholder engagement (key players) ○ Barcelona ○ Consortium – good vibes ○ Free to specialise
What held us back? ⚓ ○ Time ○ Confusion ○ Struggling alone ○ Level of detail on tasks + confusion ○ Lack of info overall project ○ Stakeholder engagement (few members) ○ Few active stakeholders ○ WPs interaction ○ Meeting without over burning ○ A little bit chaotic meeting dynamic ○ No summary of the discussions (meetings) ○ Interaction between TT at the beginning was confusing ○ Short period to do tasks (KPI example June, external factors) ○ Soil weeks structure/content (homogenization) ○ Going off topic during discussions	What are future risks? 🪨 ○ Broader views across TTs ○ Time constraints ○ Enthusiasm of stakeholders ○ Losing stakeholders ○ Harmonisation ○ Lack of objectivity if there's lack of diversity ○ Effective communication ○ Keep stakeholders engaged ○ Need of stakeholders but few times ○ Working separately ○ What is still not clear (definitions) ○ Maintaining stakeholders motivated Criteria selection, not participatory might hinder engagement Lack reviewers for the next public revision or new reviewers will lack expertise on the topic ○ Soil weeks information flow fails ○ Lack of dialogue between TT leaders and soil weeks organisation

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All this information helped to give a sense of cohesion among TTs and as a group and helped visualizing the strengths and bottlenecks suffered at a time projected timelines. All in all, invigorates the partners present.

Building on those, Leitat designed a survey to gather insights from the key stakeholders in relation to essential aspects of the project, such as stakeholder engagement, cross-fertilisation events and knowledge exchange. Additionally, more inputs were collected through the monthly meetings. On the other hand, a second questionnaire was created, but this time, it focused on collecting insights from key stakeholders. All this information served as the foundation for defining the approach used for the evaluation of the TTs.

Thereafter, a significant instance of the evaluation was conducted at the SOLO's general meeting held in Lund, Sweden in May 2025 (M30), involving the active collaboration of all TT leaders. During a three-hour session, LEITAT as WP2 leader, established a series of activities that aimed to collectively reflect on past efforts and to develop an action plan to face recurrent challenges presented in the first half part of the project till date.

The methodology used within the TTs (with key stakeholders) is divided into two steps. First a questionnaire was created to collect feedback, but this time, it focused on key stakeholders. It contained inquiries regarding key components of the project e.g. stakeholder engagement, cross-fertilisation events, and knowledge exchange. Feedback from key stakeholder is pivotal to steer the direction of the project and the TTs in the following months. The questionnaire was designed so that key stakeholders could answer and remain anonymous, providing the opportunity to share their insights freely and in an open manner. The information collected through the questionnaire was the basis for designing the workshop that took place in person.

The midterm evaluation workshop was structured around the story mapping approach[1]. The reason behind this decision was the fact that it allowed to track the journey of the TTs and it stressed the aspects that needed to be reinforced to ensure a better implementation of the project until its conclusion.

To achieve this, several activities were carried out. The first stage was to explain to the TT leaders the aim of the evaluation and its expectations. Then, each TT reflected on their own performance to identify the most significant achievements and setbacks. The results of this exercise were recorded in a A4 sheet. The next stage was to move those initial reflections into their respective virtual conceptual board (Miroboard). Within those dashboards, each TT categorised their achievements in green sticky notes and setbacks in red sticky notes taking into consideration the following items: i) internal organization, ii) stakeholder engagement, iii) communication and dissemination and iv) project implementation.

For the next stage of the dynamic, the results of the questionnaire were provided to the TT leaders. The objective of the questionnaire was to gather feedback and input from the key stakeholders in relation to key elements of the project (e.g. the cross-fertilization events, engagement and participatory activities, etc). Once the TT leaders received this feedback, they were given time to review and to reflect on this information. Then, they categorised this feedback in their respective conceptual board (achievements and setbacks but using the yellow sticky notes).

The second step focused on a plenary session in which each TT shared and exchanged thoughts and views about the results obtain through the exercise. After the presentations, a discussion took place addressing the following aspects: i) common success factors and achievements, ii) recurring challenges and setbacks, iii) opportunities (e.g. collaboration), iv) resources (lack of material, improved communication flow, etc) and shortcomings (poor engagement, unclear goals, etc). After this, a shared timeline was developed among all the participants to evaluate the actions taken so far. In this sense, TT leaders were asked to place at least one sticky note (achievements, setbacks and the input from their key stakeholders) in a column slot to highlight crucial moments within the project. Lastly, an action plan was developed in a participatory manner to identify the efforts needed in a short- and medium-term to move forward in an efficient way.

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3.2 Main lessons learned

After the first part of the workshop was completed, the focus shifted to collectively identify future actions to implemented during the second half of the project. The objective is to reinforce aspects that are currently hindering the optimal development of the project.

Through a participatory plenary session, TT leaders reflect on actions carried out so far within the project. To do this, strategic moments in time were established based on the meetings held every

[1] https://www.scrum.org/resources/blog/como-hacer-un-user-story-mapping

six months e.g. kick-off-meeting, Barcelona meeting (first cross-fertilisation event), Wageningen meeting and the insights from the discussions held on the first day of the meeting in Lund. The idea was to identify the achievements and setbacks that emerged during those exact moments. Once this was done, these were addressed collectively one by one, then, TT leaders proposed potential actions to face current challenges within the following months.

Here after we synthetise the main aspects standing out for improvement identified within the project following the abovementioned methodology. The results of the participatory activities described at the methodology subsection can be found in Annex I. Additionally, Table 5 summarizes the main points highlighted by the corresponding TTs, giving a picture of how many TTs were sustaining which points. It helps to address them with a common ground and understanding TTs specificities if any.

Table 5: Main elements highlighted by the TTs

	Maintaining stakeholder engagement	Enhancements to the ARPHA platform	Collaborative agenda development	Agenda planning to prevent cognitive overload	Internal project implementation	External communication	Prioritisation methdology	Common literature review	Enhance links among the TT's work
Reduce desertification	X			X		X		X	
Soil organic carbon stocks	X	X			X	X			
Soil sealing	X				X				
Soil pollution	X	X		X	X	X	X		
Soil erosion	X	X		X	X		X	X	
Soil structure	X			X	X	X			
EU footprints on soils	X				X	X			X
Soil literacy	X	X	X				X		X
Nature conservation of soil biodiversity	X								X

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A. Stakeholder engagement

- Distinctive strengths

TT leaders have outlined favourable advancements. For instance, in general terms a very active pool of key stakeholders especially for the co-development of the outlook chapters, the number of stakeholders has increased annually. Participants report feeling motivated to engage, especially when reading the finalized outlook chapters, which highlights a sense of pride in their contributions. Additionally, they have stated that working under a participatory approach has presented a distinctive, yet positive, experience from which they have gained substantial learning.

Furthermore, it is worth noting is that each TT has a concrete number of key stakeholders that participate in a quite active manner in the co-development of the outlook chapters. In addition, key stakeholders have stated that they have felt acknowledged and that their contributions have been taken into account during this procedure, and overall, motivated and informed in relation to the project.

SOLO also highlights the creation of networks among stakeholders with special emphasis on two components, the expansion of the SNK and the extension of its duration beyond the project's lifespan. The contribution of the TTs towards reaching this has been the cultivation of collaborative spaces where mutual learning is fostered, enabling key stakeholders to feel comfortable sharing ideas and exchanging knowledge (regardless of the diverse backgrounds, expertise,

perspectives). This has facilitated the formation of connections within the TTs (participation in conferences, seminars and other activities outside SOLO) and positively influence the possibility of developing future collaborations (e.g. publication of articles and drafting of potential project proposals).

Moreover, the participation of key stakeholders in the cross-fertilisation events has enable them to observe tangible progress within their TTs and therefore, the project. They have expressed feeling being part of something. They also have encouraged other key stakeholders to take part of these events as they consider them an essential component of the project.

- Limitation and challenges

It can be observed that stakeholder engagement is one of the most challenging aspects of the project. Mapping and engaging diverse types of actors from different backgrounds and areas of expertise is a task that not only requires effort but is also critical. Project partners need and are aware of the limitations that may derive from this, for instance, stakeholder fatigue, unbalanced engagement or biased representation and short-term engagement, among others.

All TT leaders have expressed facing challenges when engaging with stakeholders highlighting two main elements: i) maintaining through time an active level of engagement within the activities carried out in the TTs and ii) involvement of certain types of actors outside the science community (both natural and social) such as farmers.

In this sense, it is key to emphasise that due the nature of the creation of the scientific-based outlook chapters, it can be challenging to integrate expert-base knowledge during this process. This is especially underscored during the literature review process, which constitutes a relevant component of the drafting procedure. On the other hand, it is key to underline that the TT leaders have identified and applied different approaches to collect feedback from key stakeholders during this process. For instance, in some cases, actors from the academia community prefer to deliver their insights through written formats rather than during online meetings, while other key stakeholders lean towards oral discussions. In this sense, it can be emphasised that TT leaders have adapted to the needs of their respective actors and have implemented concrete approaches to engage with them. Although maintaining meaningful engagement can be challenging, significant progress and dedicated efforts have been made to achieve this goal.

Figure 11 highlights the recurring aspects in relation to engagement.

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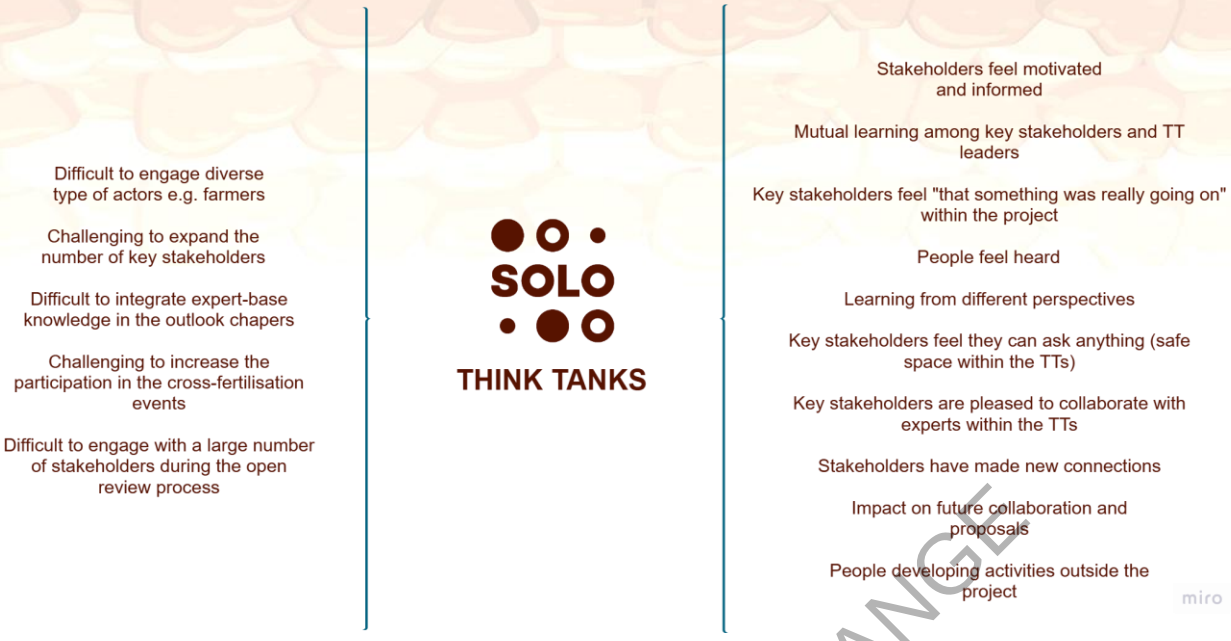

Figure 11: Negative (left) and positive aspects (right) in relation to stakeholder engagement

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To summarise the information presented regarding this theme. It is pivotal to emphasise the existing and inherent difficulties in relation to maintain an active and meaningful engagement. As stated before not only increase the number and diversify the types of stakeholders is a key component, but also, to maintain this involvement through the duration of the project. In this sense, it is important to acknowledge that TT leaders have demonstrate sustained commitment and achieved notable progress in maintaining key stakeholders engaged across multiple activities, with minimal participant loss during the first thirty months of the project, which requires substantial effort.

B. Internal project implementation

Having a well-defined approach for the internal implementation of the project is essential to ensure its effective execution. All partners must be aware of the internal workflows, alignment with specific objectives and the expected outcomes and impact. Furthermore, it will allow a better integration of the project results and across WPs, as well as to foresee any possible deviations. To achieve this, key elements should be carefully considered and well-managed throughout the project lifespan. These are as follows:

- Development of a coordinated timeline for project execution

Although initial timelines and flows were shared with the TT members when inviting them and at the beginning of their involvement, internal organisation within the project must be adjusted, for instance, the introduction of a shared timeline integrating key deadlines and/or activities of all different WPs. This would improve the workflow among WPs and project partners and to prepare in advance for the required actions. Furthermore, this would benefit TT leaders in terms of communicating with key stakeholders in a more effective and timely manner.

- Collaborative agenda development through advance stakeholder engagement (cross-fertilisation events)

Key stakeholders have expressed the need to know more information in advance about the selected dates of the cross-fertilisation events. Unfortunately, due to miscellaneous circumstances this information has not been delivered in timely manner for key stakeholders to arrange their agenda accordingly. Of course, some estimation about the dates is always provided, but they are requesting for detailed information (agenda, specific dates, times, etc). SOLO partners have already taken measures to tackle this issue, therefore, the third cross-fertilisation event scheduled for autumn 2025 in Portugal was announced well ahead of time. The plan is to continue with this approach and sent "save the dates" notices to key stakeholders as soon as the dates are confirmed by the coordination team and the host partner. Furthermore, some key stakeholders have shared their intentions to be involved in the designing of the activities that would be implemented in these events.

- Adopt a strategic approach to agenda planning to prevent cognitive overload in cross-fertilisation events

Another aspect highlighted in relation to the cross-fertilisation events is the busy agenda prepared for the two days that require the participation of key stakeholders. Under this premise, there are two key aspects to be underlined: i) the nature of the activities envisaged is always aligned with the fundamental objective of the meeting and ii) the introduction of more flexible activities.

It is pivotal to keep in mind that the participation of key stakeholders in both the in-person meetings and other activities undertaken within the TTs is voluntary. Therefore, in SOLO it is essential to consider feedback.

It is crucial to address these two aspects bearing in mind diverse aspects. On one hand, the two meetings had different purposes so fit-4-purpose dynamics where designed. On the other hand, there might be diverse perspectives integrated into these statements since it combines the feedback from key stakeholders that attended both meetings and of others that participated in Barcelona, while others in Sofia. For instance, the activities planned for the meeting in Barcelona were more flexible than the ones in Sofia due the fact that it was the very first time that key stakeholders and TT leaders met in person and some items needed to be discussed in this manner (internal organisation of the TTs, governance model, etc). This also applies for the first discussions regarding the knowledge gaps not only between the key stakeholders of a respective TT but also integrating all key stakeholder present in the meeting regardless of the TT they belonged to. This is the reason behind the development of the World Café and Fishbowl dynamic. On the other hand, the meeting of Sofia was designed to enhance the content of the documents based on specific comments e.g. the introduction of graphic and figures aiming at representing visually key concepts and/or definitions, the implementation of the outlook chapter's structure and strengthen the links among the core features of the roadmap: knowledge gaps, bottlenecks and actions.

Nevertheless, listening to the needs of the key stakeholders is pivotal to avoid any risk of fatigue when participating in the activities. Finding ways to mitigate these potential challenges is necessary to maintain a balance engagement and prevent any risk of losing actors in the course of the project. Therefore, these inputs will be taken into account when planning the future cross-fertilisation events.

- Strengthening Behind-the-scenes efficiency to support project objectives

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The workflow within WPs must be reinforced. This includes internal communication channels involving all project partners and more interactions across all WPs. This matter was already addressed by the introduction for both coordination monthly meetings and the “GOING SOLO” internal meetings to ensure the proper implementation of the respective tasks and activities in a timely manner, and to foresee any risk of deviations. Furthermore, in case any of the project partners require further assistance with a specific action this can be addressed within these meetings and design a plan to approach it.

C. Elevating external communication strategies

The aim of the open review process is to reach a wider audience. This is what is defined within the project as the Soil Network of Knowledge (SNK) which is materialised through the ARPHA platform. Setbacks arose concerning communication during the last open review process (2025) in relation to the limited reviews collected during the first attempt. To mitigate this challenge a second attempt took place incorporating communication kits designed for each TT to promote their respective outlook chapter in diverse channels e.g. LinkedIn, email, and X (formerly known as Twitter). The kits included i) images to promote the process overall, ii) an image displaying a countdown of the remaining days allocated for reviewing the documents, iii) images for each TT specifically and iv) a text to be included in the main part of the social media publication.

According to the feedback received from the TT leaders, these kits, designed by project partner PENSOFT were found to be effective. Figures 12 and 13 illustrate all these diverse elements.

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Figure 12: Invitation to be a reviewer (SOLO communication kit)

Figure 13: Invitation to be a reviewer tailored for each TT (SOLO communication kit)

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D. Prioritisation setting

The initial efforts to establish a prioritisation setting for the knowledge gaps identified by each TT in relation to their respective SMO took place during the second cross-fertilisation event held in Sofia, Bulgaria in November 2024. This exercise was divided into two sections. The first one included the participation of the key stakeholders that attended the meeting in Sofia. In this sense, each person was provided with twenty-seven stickers to select the most relevant three knowledge gaps for each of the nine TTs. Then, the second part was conducted online and only the key stakeholders that did not attend the in-person meeting were able to cast their vote on the knowledge gaps through a Microsoft forms. The process was basically replicated from the exercise undertaken in Sofia.

Furthermore, it is worth stressing that one of the main limitations presented within this approach was the reduce space to conduct the activity. The space selected did not allow for 40 people to move around, read the information presented in sticky notes and cast their vote in a more thoughtful manner. Key stakeholder stated that perhaps under a more suitable space and

conditions their vote would have been different. On the other hand, although during the online prioritisation session aimed at emulating the same structure carried out in Sofia, key stakeholders mentioned that having a calmer environment to carry out the exercise was beneficial.

Based on the information collected through the survey for key stakeholders and the midterm evaluation of the TTs, it can be concluded that a clearer methodology needs to be implemented for the prioritisation setting. It was also stated that communicating in advance the procedure to follow would be quite helpful for stakeholders in order to perform the procedure accordingly and no to overwhelm them with the dense information that would be prioritised. SOLO's goal in the upcoming months is to propose a methodology to carry out this procedure in the next cycles. Having an established methodology with well-defined criteria for prioritisation would improve the content of the roadmaps.

E. Enhancements to the functionality and usability of the ARPHA Platform

Two open review process rounds have been carried out and critical aspects have been highlighted by both the TT leaders and the reviewers. One of the main matters reiterated is the complexity to include the overview table that includes all the knowledge gaps, bottlenecks and actions within the platform to be visible for reviewers when revising the documents. To address this issue, the PENSOFT team has implemented the action of uploading the table as complementary document (PDF file). Although, reviewers have stated that this solution is not user-friendly.

Another technical issue was recently experienced regarding the role of subject editor. In this sense, once the TTs have submitted the version for the open review process, this must be checked and approved by the subject editor (in this case, the project coordinator) so they could be released within the platform for revision. During the second round a glitch emerged that did not notify the subject editor about the submission, therefore, these documents were approved automatically. This had an impact on the timing of the open review process since no notification was sent by the platform.

On the other hand, the General Consortium meeting held in Lund in M30, WP2, WP3 and WP4 leaders gathered with PENSOFT (WP1 leaders) to examine the structure and functionality of the SOLO website and the ARPHA platform to highlight aspects to be improved and provide some suggestions. WP2 feedback held on the range of comments and experiences collected from TT leaders based on submitting and editing the outlook chapters into the platform.

Moreover, PENSOFT provided support via emails and by holding meetings with TT leaders during the submission phase. Ensuring the well-functioning of the platform is pivotal for SOLO since the interactions within SNK materialises there.

F. Elevating document structure and content for enhanced coherence and impact

Two main measures have been implemented to enhance the content and structure of the documents co-developed in each TT. First, the coordination team created a template to restructure the content of the documents, thereby ensuring a more cohesive and coherent reading that facilitates better understanding. The idea is that each document produced in the TTs is conceived as a chapter within a larger volume, which collectively constitutes the Outlook for Soil Health 2025. The second action implemented was to undertake an internal review of the outlook chapters among TTs to ensure that TT leaders delve deeper into the work carried out in other

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TTs, the identified top three knowledge gaps and the approach adopted to structure their documents to ensure harmonization among all of them.

Coordination team proposed that each TT has to review 3 other documents. To do this, WP2 leaders suggested a distribution based on the allocation of the Soil Weeks and Regional Nodes events, so this information could be used for purpose of planning such events. Nonetheless, it was highlighted that some topics might be of equal relevance to various TTs. Considering this, the distribution was done in the most equitable manner possible for all parties involved. After sharing it with the TT leaders, they were asked if they agreed with the proposal. Table 6 presents the final allocation:

Table 6: Final allocation for internal review among TTs

PROPOSED DISTRIBUTION FOR REVIEW OF SCOPING DOCUMENTS AMONG THINK TANKS				
THINK TANK	OTHER THINK TANKS SCOPING DOCUMENTS			
	1	2	3	Observations
LAND DEGRADATION	Soil organic carbon stocks	Soil Literacy	Footprint on soils	Confimed by TT leaders
SOIL ORGANIC CARBON STOCKS	Soil structure	Soil Pollution	Nature conservation of soil biodiversity	Confirmed by TT leaders
SOIL SEALING	Land degradation	Soil literacy	Soil erosion	Confimed by TT leaders
SOIL EROSION	Land degradation	Soil organic carbon stocks	Nature conservation of soil biodiversity	Confirmed by TT leaders
SOIL POLLUTION	Soil erosion	Land degradation	Soil structure	Confirmed by TT leaders
SOIL STRUCTURE	Footprints on soil	Soil literacy	Soil organic carbon stocks	Confirmed by TT leaders
FOOTPRINTS ON SOIL	Nature conservation of soil biodiversity	Soil sealing	Soil structure	Confirmed by TT leaders
SOIL LITERACY	Footprints on soils	Soil sealing	Soil pollution	Confirmed by TT leaders
NATURE CONSERVATION OF SOIL BIODIVERSITY	Soil sealing	Soil pollution	Soil erosion	Confirmed by TT leaders

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4 Next steps

4.1 Next steps

This section focuses on the definition of the following steps to be implemented in the second part of the project. These will mitigate essential features that were highlighted reiteratively through the diverse reflexive dynamics and activities by both TT leaders and key stakeholders. Furthermore, feedback from key stakeholders that were shared in their TTs internal meetings was considered. It is important to note that these internal meetings are scheduled based on the needs of each TT and their key stakeholders. At least, they hold a meeting before and after the cross-fertilisation events to share main insights and before and after the co-development of the outlook chapters so all key stakeholders can contribute to drafting and review process.

Figure 14 emphasises the connection between the lessons learned during the first 18 months of SOLO and the prospective measures to be undertaken in addressing the previously identified hurdles. Then, a description of each of the measures is provided. Due to the nature of some of the actions presented in this deliverable, further discussion involving project partners and even key stakeholders is required, for instance, the prioritisation methodology. This will take place in the next meeting scheduled for autumn 2025 in Evora, Portugal.

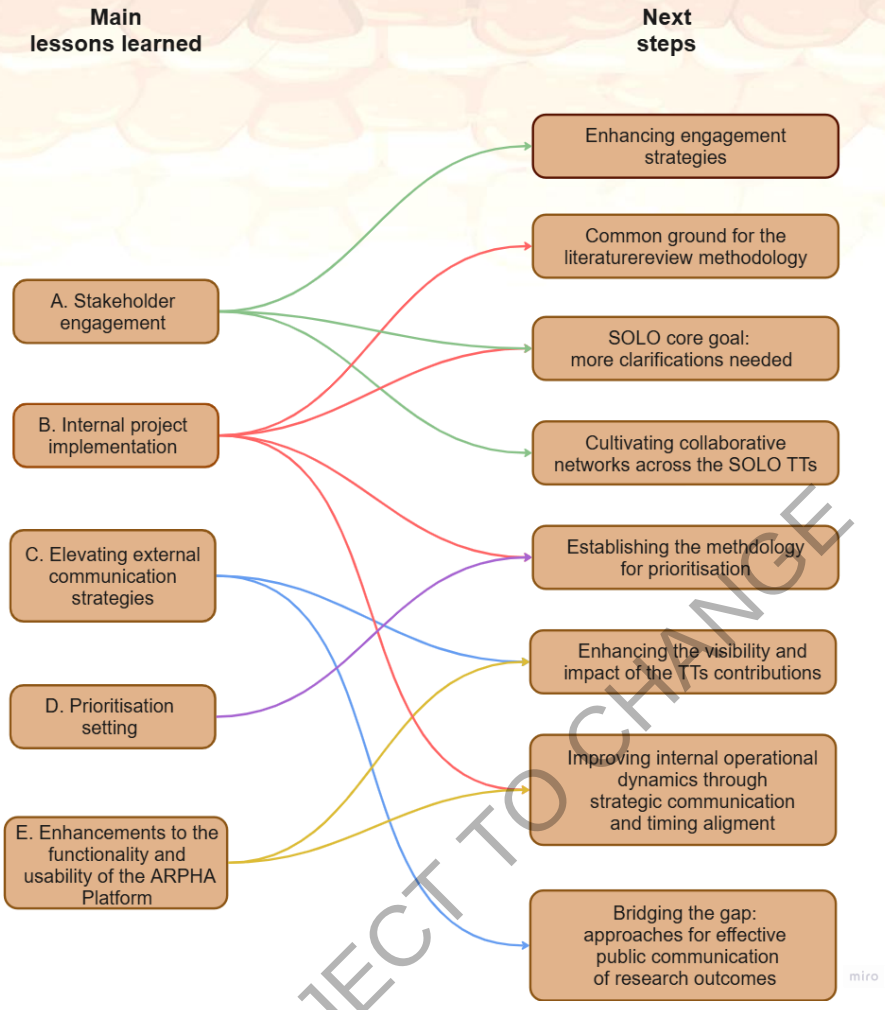

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Figure 14: Link between the main lessons learned and next steps in SOLO

- SOLO core goal: more clarifications needed

Diverse stakeholders involved within the TTs, and hence, the SOLO project have outlined the lack of a common understanding of the project. This might have implications regarding stakeholder engagement. It goes without saying that actors are more involved whenever they have a comprehensive understanding of the research project. In this sense, efforts must be made to communicate what is our ultimate goal, the impact and the legacy of SOLO.

Developing a clear understanding of the project's direction and intended impact is crucial, not only for guiding its development but also for enabling precise and effective communication with key stakeholders. They are the core of the project, and therefore, they need to have a clear understanding of these main aspects. In this sense, this aspect is required to be reinforced. A concise introduction or presentation of SOLO delivered by the coordination team during the cross-fertilisation events with key stakeholders could serve as a valuable measure to address this matter. Furthermore, an explanation of how each of the diverse workshops that will take place in these events contribute to progress towards this goal could be beneficial.

- Enhancing engagement strategies

One of the ideas to diversify and increase the number of potential key stakeholders to be involved within the TTs, is the creation of the stakeholder monitoring tool. This tool will allow to aggregate information about contacts and will be built on a recommendation-based logic. For instance, if one member of a certain TT has information about a person that could be interested in participating as key stakeholders in other one of the TTs, then they can add this information into a shared database created for this purpose. There might be occasions in which key stakeholders and/or TT leaders might have colleagues that could be interested in participating in the project, however, due to their specific expertise, they may not be suited for direct involvement in a particular TT. Instead, their background and area of knowledge might align more appropriately with other TTs focusing on different topic. Therefore, the creation and continuous update of this database would be valuable for collecting this information to facilitate consultation. This action also mitigates one of the issues highlighted by the TTs, which is the lack of expertise in relation to concrete topics.

- Enhancing the visibility and impact of the TTs contributions

A key area requiring further emphasis is the development of a clear strategy to enhance the visibility of the TTs' work. For instance, the introduction of small sessions in which they present or explain in a dynamic manner the outcomes obtained so far and key messages to explore potential pathways for further collaboration among TTs. Moreover, this visualisation should also aim to a wider audience targeting actors outside the project.

Making work visible increases awareness of the TTs contributions and impact in relation to the targets embedded in the SMOs. This also has a positive effect in relation to the motivation of TTs and key stakeholders as it reinforces a sense of value and reduces uncertainty. Knowing that their efforts are acknowledged and appreciated can drive them to maintain or increase their performance.

In addition, results visibility could potentially enhance interactions among the SOLO TTs. Under this line, this open visibility might encourage TT leaders to learn and provide support to one another, thus, fostering a collaborative culture emphasizing that TTs are driven by collective achievements.

During the second co-production of the TT’s documents, the outlook chapter of the Reduce EU footprints on soil was selected and used by the Commission. The TT leader shared some key points with other TTs to explain the process of co-development that was carried out, as well as the structure and content of the document itself.

Generally speaking, these types of actions nurture an environment where both TT leaders and key stakeholders feel motivated and accountable in relation to the work performed and where are empowered to achieve their best work together.

- Improving internal operational dynamics through strategic communication and timing alignment

As it was addressed before, the introduction of communication kits for each TT to be used during the promote open review process of their respective documents is one of the measures that was taken during this second round. Each TT was provided with tailored visuals and messages to reach their appropriate and intended audience.

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Furthermore, key stakeholders highlighted that the introduction of newsletter regarding the TTs they are involved in, and the SOLO project in general would be an interesting action to keep actors engaged and informed regarding the main activities taking place.

It is essential to consider the potential for overwhelming key stakeholders by frequently disseminating excessive amounts of information. Consequently, it is advisable to distribute the newsletter on a bimonthly or, if necessary, a monthly basis. Additionally, the content would be organised in bullet point format.

- Establish the methodology for prioritisation

It has been stated by both TT leaders and key stakeholders that a well-defined methodology needs to be integrated for the prioritisation of the identified knowledge gaps in each TT. The criteria and method have not yet been established. A first exercise was undertaken in 2024, but it did not follow previous drafts nor deliver a concrete procedure. As SOLO is based on an iterative process, its nature would allow for improvement of certain processes. In this regard, the methodology will be defined in the upcoming months. Nevertheless, it is essential to involve project partners in the development of the methodology. Not only this matter is of particular relevance for TT leaders as it will impact the priority of the knowledge gaps, but also because it holds significance for the key stakeholders involved, who actively contributed to the gap identification process.

- Cultivating collaborative networks across the SOLO Think Tanks

According to both TT leaders and key stakeholders there is the need of strengthening interactions among all the TTs. There are two suggested actions to be implemented, for instance, holding bilateral internal meetings among TTs. The objective of these meetings would be to explore the feasibility of linking all the work developed so far within each TT since each SMO is related to each other. Additionally, this would have a favourable effect on the outcome of the outlook by contributing to the establishment of a more coherent structural flow.

During the evaluation of the TTs, some of the leaders have articulated that through the implementation of their respective Soil Weeks events, they have managed to reach out and involve more stakeholders into their TTs. Furthermore, TT leaders have also reached out to organisations that later developed a relationship with the TT and together participated in conferences and/or workshops. Additionally, this also allows to disseminate the work carried out within SOLO.

- Bridging the gap: approaches for effective public communication of research outcomes (translate our scientific approach to a broad mass)

Messages and communication must be tailored according to the intended audience. This would improve communication effectiveness in terms of ensuring that the message is relevant and relates to the interests and expectations of the respective public. Using an adequate tone and language for each target group increases understanding and make it more feasible for them to retain the message.

This also encompasses actors such as policymakers. Accordingly, research findings should be articulated with clarity and structured around key messages to facilitate comprehension and enhance their visibility and impact. Due the nature of their roles, policymakers often have limited time available. Therefore, tailoring the message to their specific needs and language increases the possibility that the information will be both accessed and utilized by them.

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- Common ground for the literature review methodology

TT leaders have expressed the need for the introduction of a common literature review methodology for the drafting process of the outlook chapters. This will have a positive impact in terms of ensuring consistency in terminology, in the content of the documents and conceptual frameworks. It will clarify key concepts, theories and methodologies relevant to the project, helping reducing ambiguity and potential misinterpretations. Moreover, it can facilitate communication among actors from diverse backgrounds and expertise enhancing knowledge sharing. In summary, it serves as a foundational tool that aligns understanding, fosters collaboration and increase the opportunities of achieving shared goals.

5 Acknowledgements

This deliverable incorporates multiple versions of drafts developed by each TT in collaboration with their respective key stakeholders addressing the current state-of-the-art of their Soil Mission Objective as well as the pre-identified and prioritised knowledge gaps.

On behalf of the Soils for Europe project, we would like to express our gratitude to our TT leaders and their respective key stakeholders for their contributions and all the effort put into the internal discussions, online meetings and the drafting process that led to the final version of the 2025 roadmap and outlook chapter.

Special recognition to those who kindly and actively participated in the face-to-face meeting held in Sofia in 2024 and actively involved in the periodic TT meetings and activities. Their commitment, insights and feedback collected throughout the discussions and diverse participatory dynamics were extremely valuable.

Hoping to maintain and strengthen these ties during the project's lifespan. A huge thank to all stakeholders of each TT.

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SUBJECT TO CHANGE

7 Annex I

Milestone 10: Midterm evaluation of the Think Tanks – Workshop organised during the General Assembly and input collected for D2.4

Results

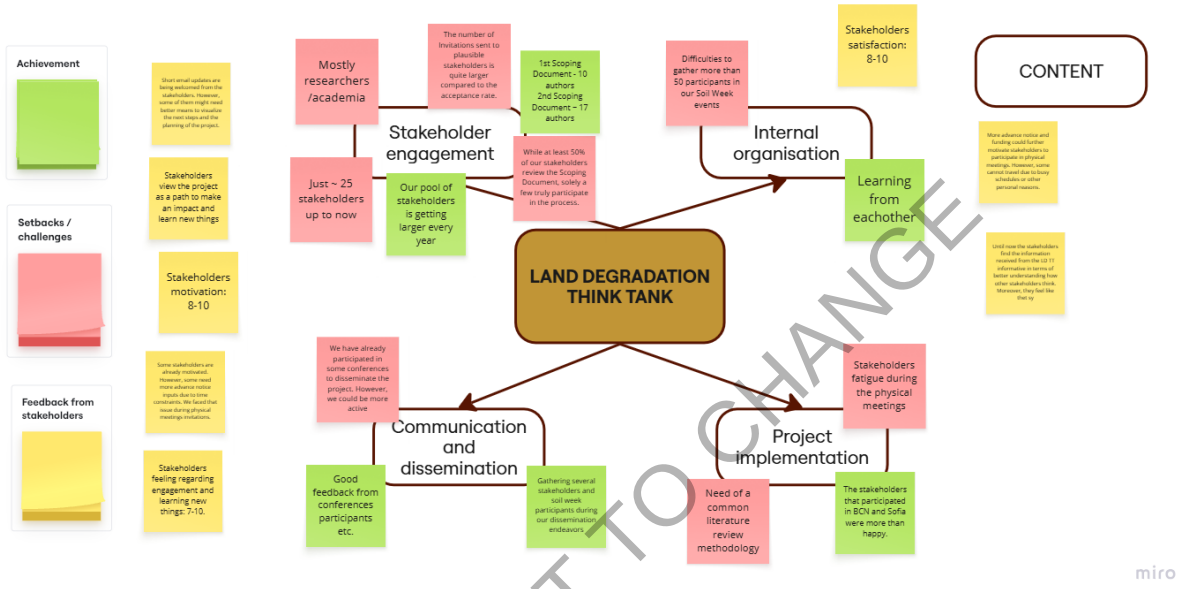

Figure 15: Reduce desertification TT board

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As described above, all TT leaders developed their own conceptual board, in which they highlighted critical aspects of the project (achievements and setbacks) as well as the feedback from their key stakeholders. In total, 9 boards were created, each per TT.

For the *reduce desertification TT*, for instance, the leaders highlighted that mostly the stakeholders engaged within the TT are from the academia sector, but the diversity and number is increasing. For example, this is reflected in the number of authors involved in the drafting of the outlook chapter (from 10 to 17, currently). Although, more than 50% review the document, but the other 50% is not that involved (e.g. only provided some literature and articles)

Furthermore, this TT has expressed the necessity of having a common literature review methodology in order to compare the literature analysis across all TTs. On the other hand, another important aspect to be outlined is the complexity of engaging stakeholders. This does not solemnly focus on the number of stakeholders involved, but it also refers to maintaining an active level of engagement during the project's lifespan taking into account elements that might hinder it, such as stakeholder fatigue.

Based on the results of the questionnaire, the key stakeholders from the land degradation TT feel motivated, engaged and informed. They also stated that they have managed to create new connections through the SOLO project.

Figure 15 presents all the information that was collected and discussed during the mid-term evaluation in relation to the land degradation TT.

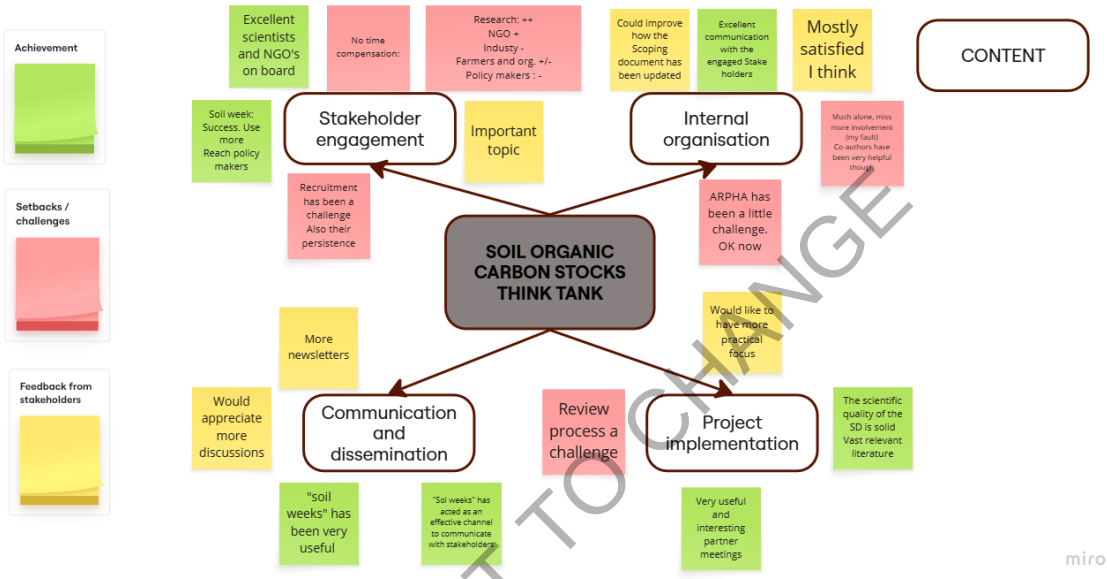

Figure 16: Soil organic carbon stock TT board

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The *soil organic carbon stocks TT* stated that the process of engaging stakeholders that are not from the academic community is quite challenging. Involving actors such as scientists is easier compared to other types of stakeholders (e.g. farmers and industry). Nevertheless, currently engaged stakeholders are mostly satisfied. Moreover, the communication flow with key stakeholders within the TT is excellent. Nevertheless, key stakeholders have stated that sending newsletters including important information about the TT and the project (e.g. deadlines, updates, news) would be a positive action to be incorporated.

Efforts will be put in place to diversify stakeholders. On the other hand, the open review process remains a challenge, especially due the fact of reaching reviewers outside the TTs and project's main networks. On this note, it is worth noting that improvements on the ARPHA platform have been carried out to make it more user-friendly.

Regarding the outlook chapter, the quality of the document is high as it contains a solid and relevant literature. Furthermore, key stakeholders are quite motivated to revise the knowledge gaps regarding this topic.

Furthermore, the soil weeks events organised by this TT have been interesting experiences in which people are motivated to have active discussions. Additionally, this TT has managed to engage with policymakers within these events.

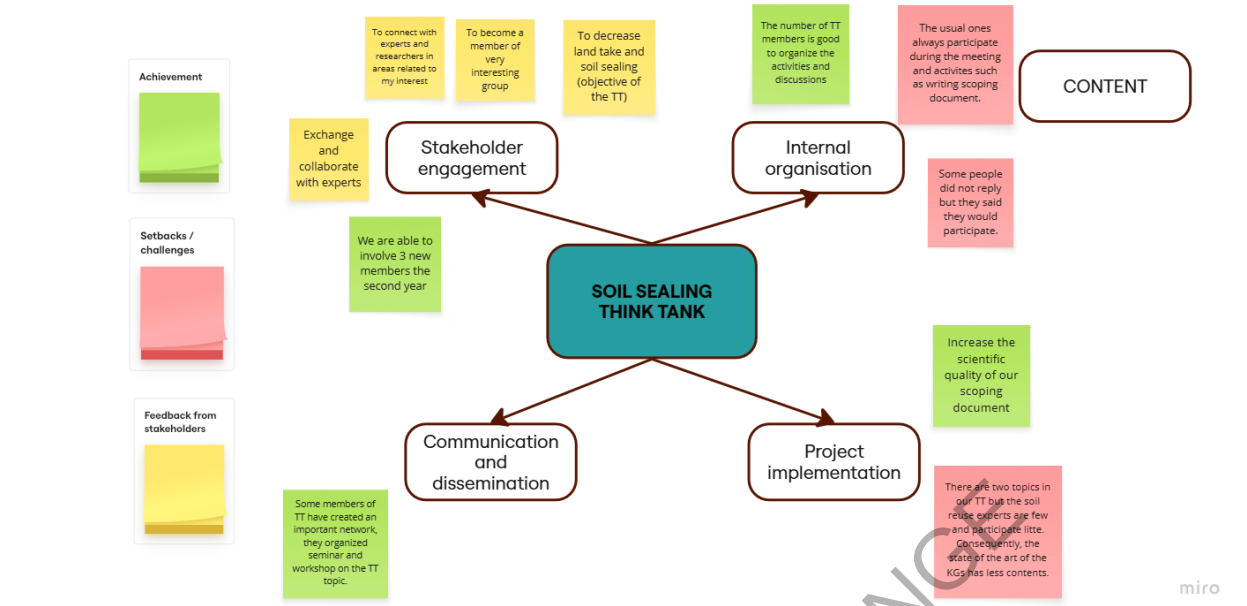

Figure 17: Soil sealing TT board

SUBJECT TO CHANGE

The *soil sealing TT* has expressed concerns about the fact that there are two topics to be addressed, especially since the experts of the topic "soil reuse" are only a few and their involvement is not quite active. This has had an impact on the content of the state-of-the-art and identified knowledge gaps addressing this topic. On the other hand, the stakeholders involved within the TT work e.g. drafting of the scoping documents are the usual ones. It has been challenging to involve more stakeholders in such activities. Currently, the TT is composed of 20 key members, although some of them are not very responsive via email.

In addition, the key stakeholders value positively to be part of the soil sealing and urban soils TT. They have managed to create connections and networks beyond the scope of the TT. For instance, they organised a seminar and workshop based on the theme and work carried out in the TT.

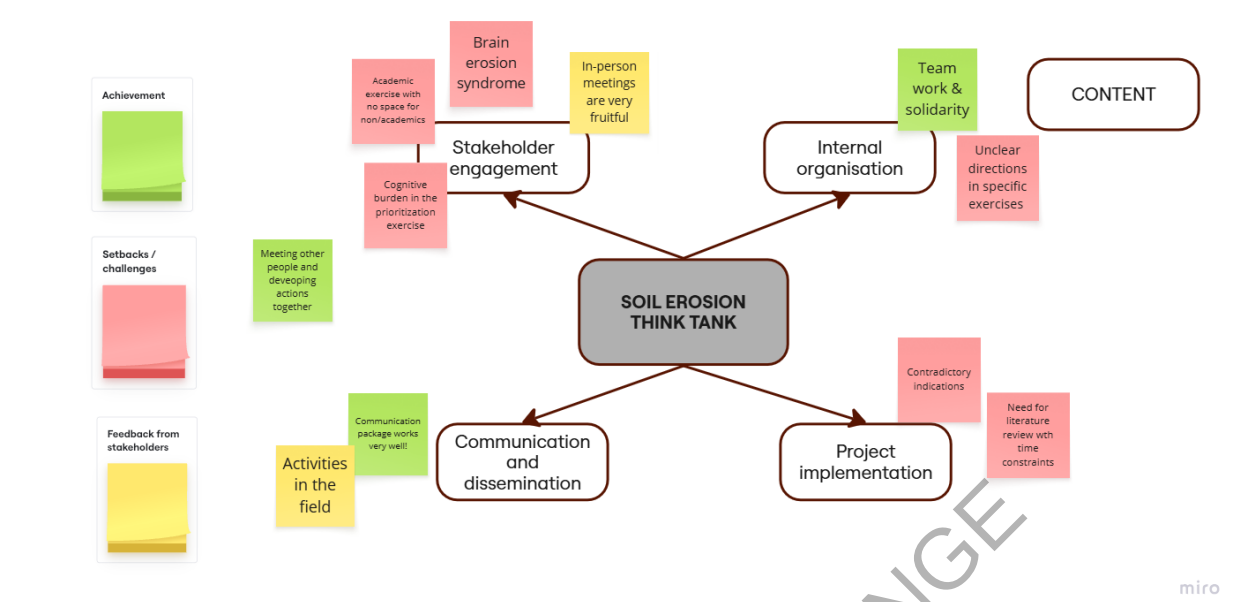

Figure 18: Soil erosion TT board

One of the main concerns presented by the *soil erosion TT* is that the drafting of the outlook chapter is a very academic exercise and due to its nature on some occasions it can be difficult to engage other types of actors e.g. farmers, especially as the outlook needed to be more literature based, which hardly allowed any opportunity to include expert-based knowledge from stakeholders that are from outside academia. Additionally, they also highlighted that most academic / research actors are from Portugal, raising interest in engaging with other actors from different countries.

As well as in other TTs, the key stakeholders of this TT have developed further connections and have collaborated in other actions together, such as in conferences. It is also outlined that the cross-fertilisation events (in-person meetings) are highly valued among the key stakeholders. They enjoy participating and hearing about the work developed in the other TTs.

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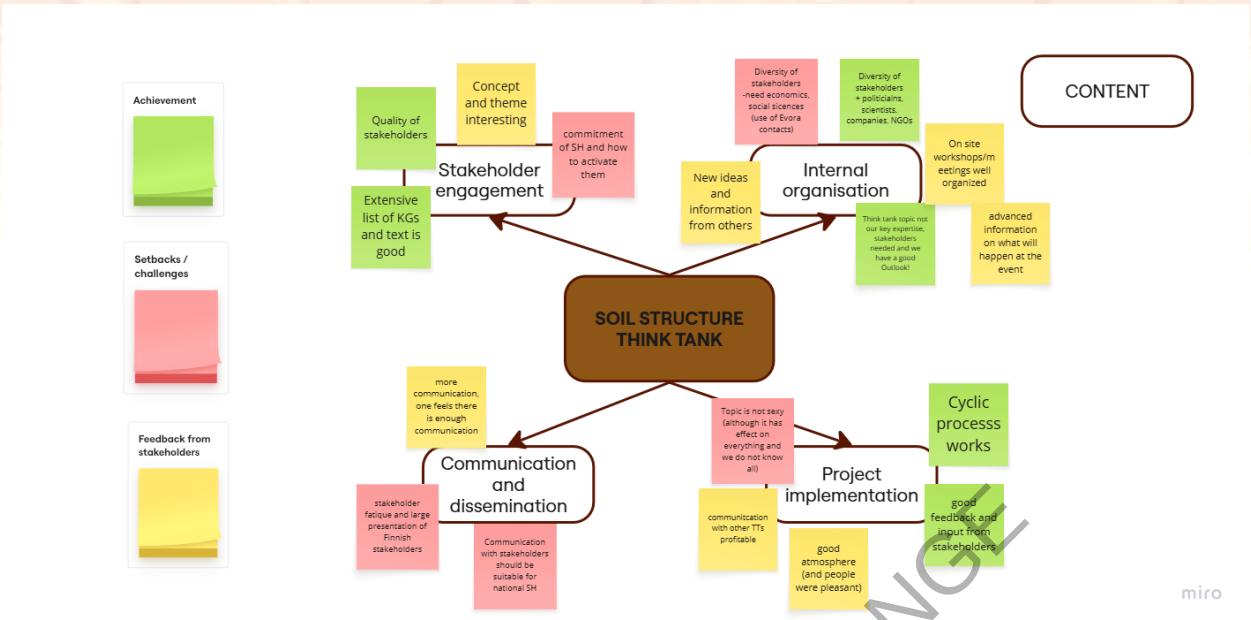

Figure 19: Soil structure TT board

The *soil structure TT* has expressed concern due the fact that they do not have an extensive variety of stakeholders and a large representation from Finland, highlighting the need to engage with actors from economic and social sciences and other countries. One line of action to address this matter is to use contacts from project partners to try to contact and involve these types of stakeholders. Nevertheless, the quality of actors involved is high and their contributions to the outlook chapter and the roadmaps is highly valued. On the other hand, the issue of stakeholder fatigue has also been articulated by this TT, but the feedback received by their key stakeholders is quite positive.

Key stakeholders have also mentioned the benefits of participating in the cross-fertilisation events (Barcelona and Sofia in-person meetings) for instance, the opportunity to exchange knowledge with other TTs and its members, and to understand better the work carried by other TTs, and therefore, the project. Nonetheless, information about the dates and activities that will be taking place should be shared beforehand so that key stakeholders know in advance what to expect.

In relation to the project implementation, this TT has pointed out that the SOLO's iterative process is functioning accordingly.

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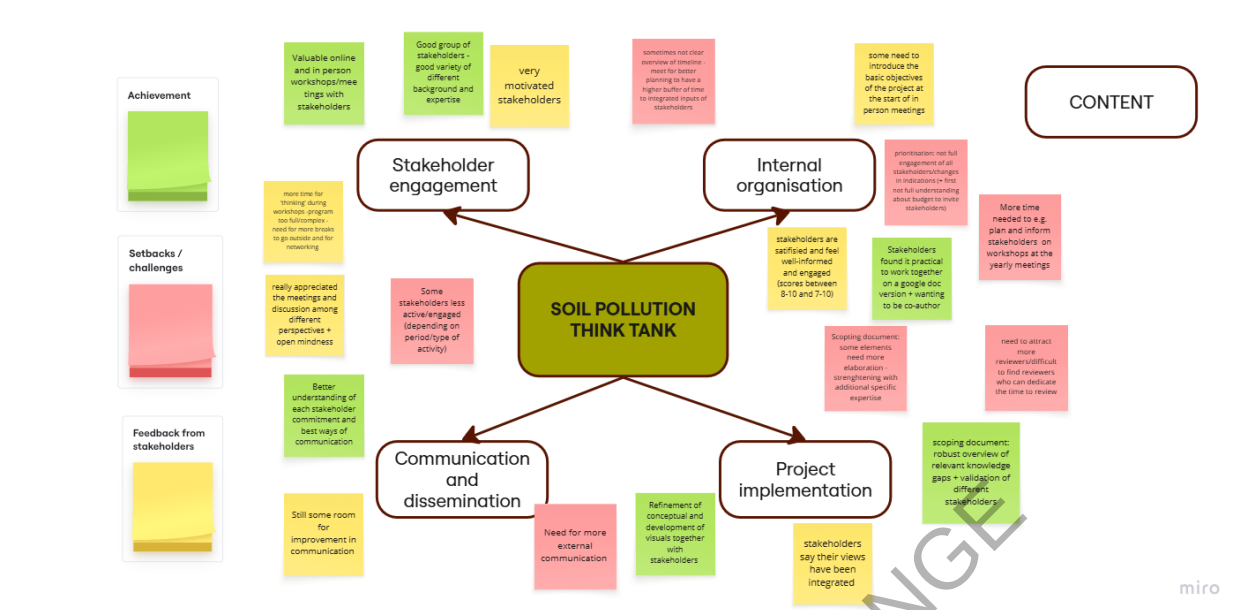

Figure 20: Soil pollution TT board

The *Soil Pollution TT* also emphasised some aspects related to stakeholder engagement. In this regard, they underlined within their TT they have a good pool of actors varying from diverse backgrounds and expertise. Having an active diversity of stakeholders has a positive impact within the TT since it not only facilitates knowledge exchange but also contributes to quality of the documents and roadmap produced by the TT, for instance, the session to co-create the figures to be incorporated in the outlook chapter. Furthermore, stakeholders have stated the value of having both online and face-to-face workshops, mainly the opportunity to engage with other stakeholders from other TTs. Nonetheless, TT leaders expressed the necessity to elaborate better the documents by strengthening connections with additional specific expertise on the subject. Key stakeholders indicated they felt comfortable participating in all the activities as the group is open-minded and did not perceive any judgement when expressing their thoughts and views.

The open review process was also an interesting matter that was addressed. For instance, TT leaders emphasized the complexity of involving external reviewers to revise the outlook chapters and provide insightful feedback.

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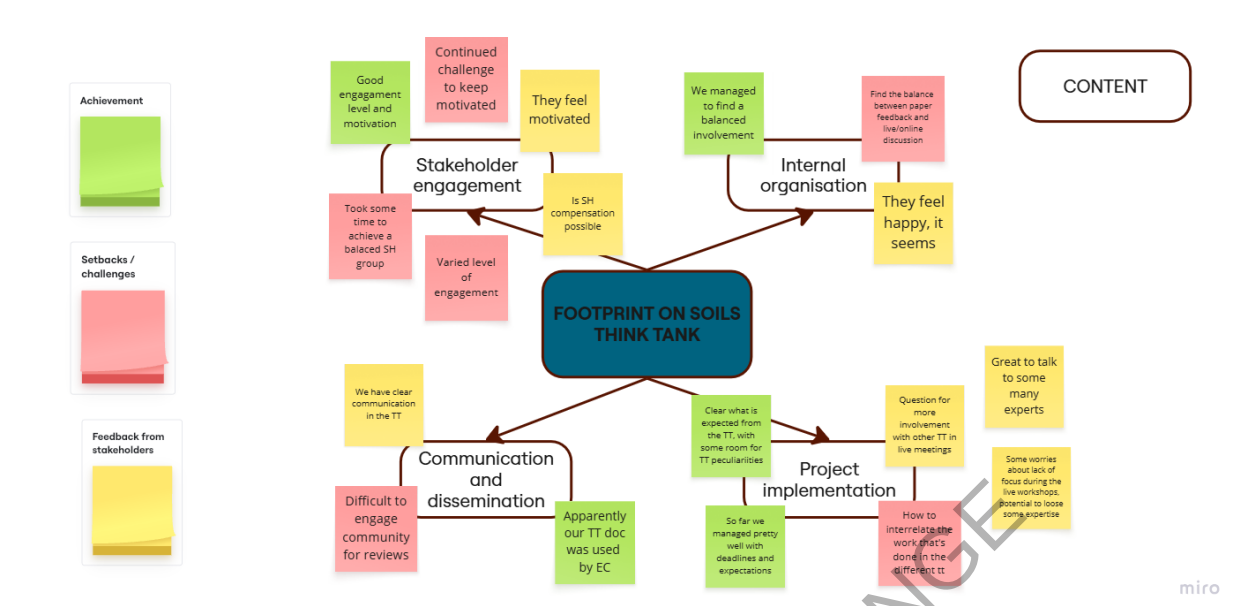

Figure 21: Footprints on soil TT board

The *footprints on soil TT* expressed that key stakeholders are motivated and engaged in the activities undertaken. However, there are two matters to take into account: i) it required considerable time to build up a balanced group of stakeholders and ii) although the level of engagement is good, not all key stakeholders can be actively involved. Additionally, the process of mapping and involvement of actors with high experience on soil footprint has been challenging.

In general terms, key stakeholders are motivated, but maintaining the level of motivation during the project lifespan is also one of the recurrent issues brought not only by this TT, but also by all of them. On the other hand, regarding project implementation matters, the footprints on soil TT has highlighted the need to interconnect all the work achieved by all the TTs, which is a subject that has also been addressed by the key stakeholders.

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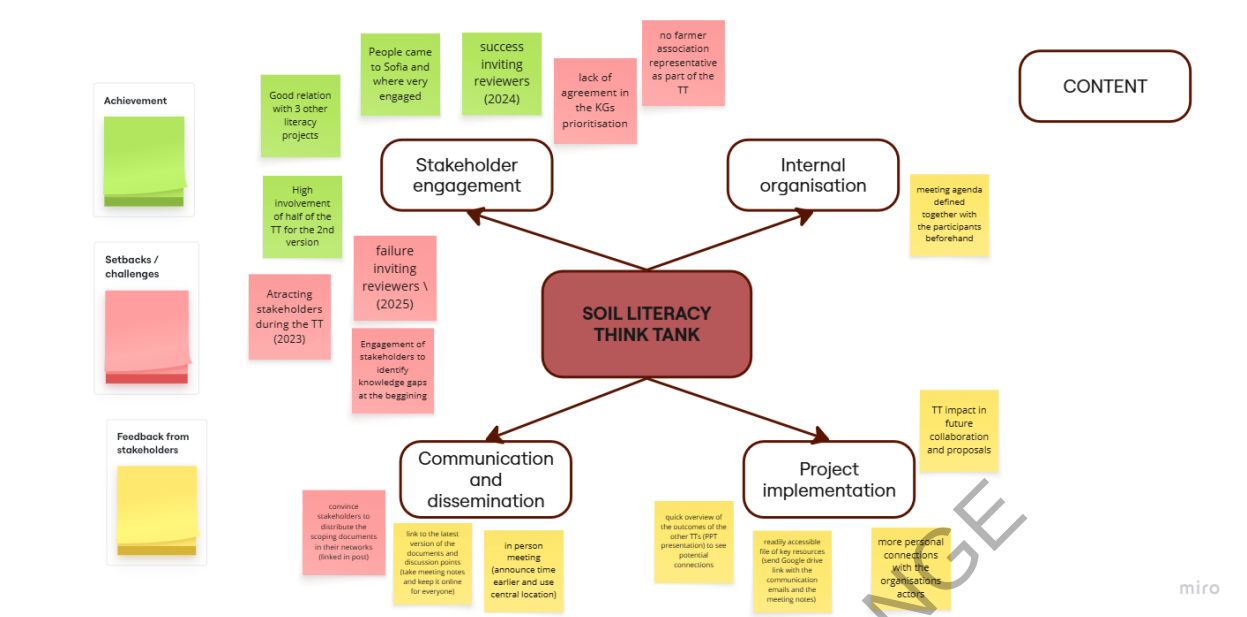

Figure 22: Soil literacy TT board

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The *soil literacy TT* also emphasized aspect related to stakeholder engagement. In this regard, they highlighted two critical situations: i) the difficulty of inviting stakeholders during the first cross-fertilisation event held in Barcelona and ii) the complexity of having reviewers for the 2025 cycle, which was not the case for the 2024 edition. Nevertheless, the number of key stakeholders that attended the event in Sofia was significant and were quite active during the diverse activities that were carried out during the meeting. Furthermore, through this in-person meeting, the relationship among other three other soil literacy projects were established. In relation to the diversity of key stakeholders, the soil literacy TT has expressed that currently no farmer association representative is involved. Efforts need to be made in the following months to reach to this type of actor.

Regarding project implementation, the key stakeholders expressed they would appreciate having an overview of the other TTs in order to identify potential synergies. Moreover, they emphasized the need of communicating key dates, such as the in-person meetings so that they can arrange their agendas in advance. Lastly, key stakeholders stated to be pleased with the internal organisation of the TT, for instance, organisation and easy access to important documents and information.

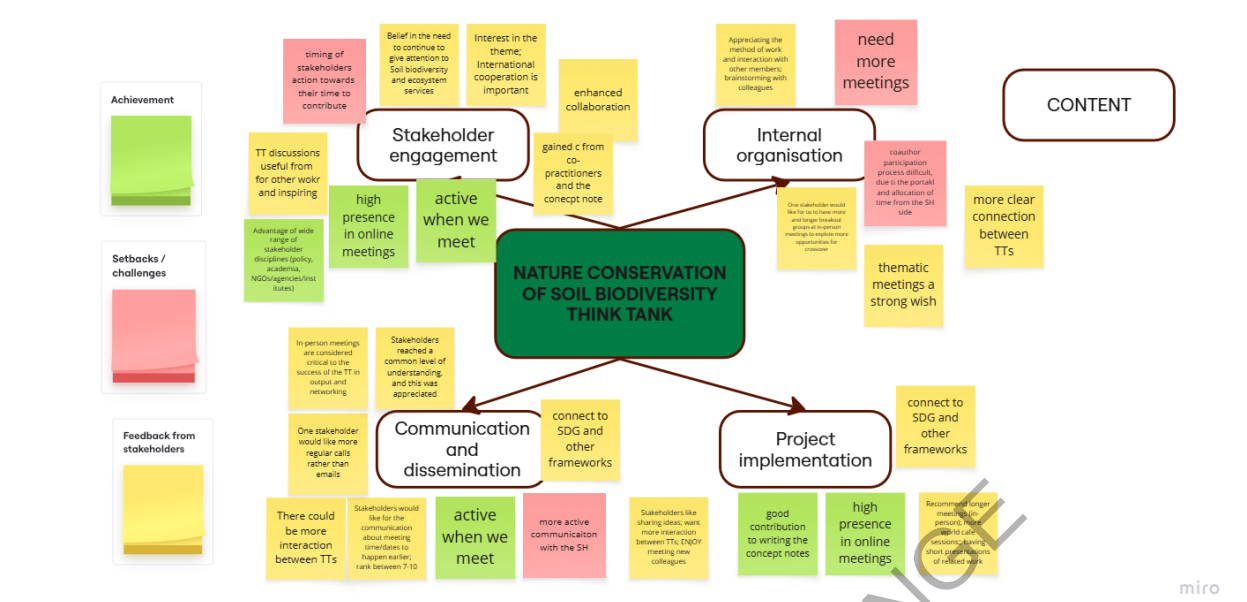

Figure 23: Nature conservation of soil biodiversity TT board

Key stakeholders of the *nature conservation of soil biodiversity TT* are strongly interest in the topic and in the need to continue working towards soil biodiversity and ecosystem services. They have also expressed that discussions that emerged in the framework of the TT have been useful and inspiring for the key stakeholders' own research and work. This translates into the active participation of key stakeholders during online meetings and involvement within the TT e.g. brainstorming sessions, in which they can interact with other members and hear diverse point of views. In this sense, they have stated that a common level of understanding has been achieved. Furthermore, this TT is constituted by a diverse group of actors ranging from policy, academia, NGOs, agencies and institutes.

On the other hand, the cross-fertilisation events are considered critical by the key stakeholders as they provide the opportunity to enhance the outputs of the project and to network. Moreover, the type of dynamics in which they can discuss in a flexible and open manner e.g. world café sessions also having short presentations about the work developed so far by other TT so they can exchange ideas and knowledge.

Another crucial aspect that emerged related to the project during the evaluation is the complexity of the co-authorship process within the ARPHA platform due the technical issues experienced so far. This has had an impact on the open review process itself and the willingness of actors to provide their input, especially because of the time needed to do so. In addition, they outlined their preference for having more interactions with other TTs and to have meetings in which they could participate based on a specific topic.

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