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SOLO Soils for Europe

Soil Mission Research & Innovation Roadmaps: a synthesis across Mission Objectives

Deliverable D2.3

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SOLO
Soils for Europe

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Summary

The following report establishes the first synthesis of the roadmaps developed under SOLO Think Tanks (TTs) for the first year of the project, the transdisciplinary co-produced and actionable R&I Roadmaps per Soil Mission Objective for future soil-related research activities in the EU. These roadmaps developed by the TTs are the key outputs of the project which will derive into an overarching roadmap in the future. Here the first attempt of all the work carried out is presented as an initial steps of an iterative process of another 4 years.

First, the constitution and engagement of TTs members was crucial for the collaborative endeavour developed. Equally important the conceptualization, structure, and governance of the TT. A small recap of the process is included in this deliverable (to be used together with the description of the TT guidelines D2.1 and Terms of Reference in D2.2). With that base, the TT leaders and key stakeholders that conform the TTs co-developed knowledge by means of the drafts co-produced, online meetings and face-to-face workshops and discussions that populate the initial Knowledge GAPs associated with the state of the art per each TT, and therefore each specific Soil Mission Objective, SMO.

Finally, each TT description and state of the art is related to diverse typologies of Knowledge and actionable GAPs per SMO. Those are related to major recent and ongoing R&I projects and major international initiatives. How are they going to be involved into the project is a next step to be discussed and incorporated into the next versions of the project and roadmaps.

List of abbreviations

EU	European Union
KPIs	Key Performance Indicators
LD	Land Degradation
R&I	Research and Innovation
RN	Regional Nodes
RRI	Responsible Research and Innovation
SMO	Soil Mission Objectives
SNK	Soil Network of Knowledge
SOLO	Soils 4 Europe Project
ToR	Terms of Reference
TT	Think Tank

1 Introduction

This deliverable aims at displaying the first attempt from all the SOLO Think Tanks work carried out during the initial period of the SOLO project (15 months). The TT leaders and key stakeholders co-developed knowledge by means of the drafts co-produced, online meetings and face-to-face workshops and discussions.

The foundations and common ground were given by D2.1(*Guidelines for the development of the Think Tanks and Soil Network of Knowledge Strategy*) and D2.2 *(Terms of Reference).* The overall process was initiated creating the Think Tanks and populating them, developing a scoping document in which the state-of-play and the main GAPs have been initially described and an attempt of a first roadmap populated by GAPs has been made including in many cases with related actions and barriers.

In situ discussions intra and inter TTs have been developed by a myriad of stakeholders during the Barcelona workshops (5th to 7th of December 2024) and the results are incorporated into new working versions developed by each TT and into this document. Those insights discussed and refined have been incorporated already and initial roadmaps have been drafted, discussed, and improved prior to develop an overall in-depth synthesis (incoming task in WP4).

1.1 Project background

The main goal of SOLO is to deliver actionable transdisciplinary roadmaps for future soil-related research activities in the EU, which contribute to achieving the objectives of the Soil Mission. This will be done by working on three axes: i) identification of the major knowledge gaps in research, driving forces and bottlenecks (10 Think Tanks); ii) assessment of synergies and trade-offs between the roadmaps of the Soil Mission Objectives and European regions (Regional Nodes), and iii) co-development of an Operational Framework and a set of indicators to monitor the Soil Mission progress.

Concisely, the Soil Mission Think Tanks aim to identify knowledge gaps and novel avenues for European soil research, innovation, and other actions in the context of the Soil Mission objectives. The Think Tanks goals as trigger and deployment of participative action research processes are:

- Co-develop the Mission Objective roadmaps,
- Facilitate co-production of knowledge,
- Establish a strong connection to current and future EU and international Soil Health projects.

The knowledge gaps and novel avenues that SOLO synthetise are related with the following Think Tanks addressing the 8 Soil Mission Objectives plus two added value TTs:

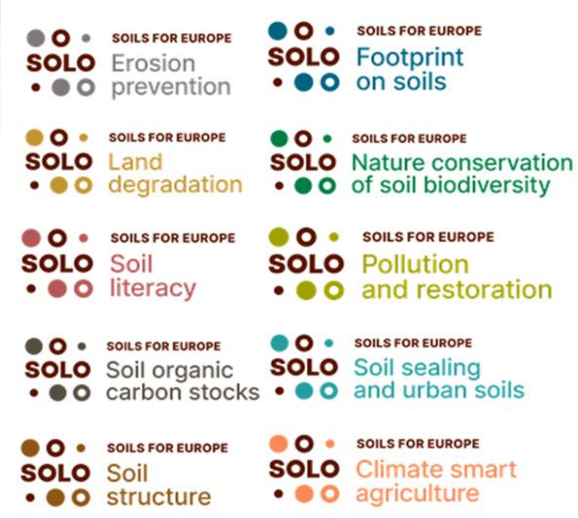

Figure 1: SOLO Think Tanks

1.1.1 Think Tanks main goals and expected achievements.

The SOLO Think Tanks are understood as knowledge-based lobby groups with the aim to develop a visionary roadmap to the future of research and innovation in Europe through a double path: 1) constant interaction with several European bodies and 2) a constant update of the main knowledge gaps found. For that purpose, the different Think Tanks aim primarily to deliver through the course of the project but specially by 2027, an actionable trans-disciplinary roadmap for future soil-related research activities in the EU that contribute to achieving the objectives of the Soil Mission. This implies identifying knowledge gaps, drivers, and bottlenecks that may hinder or create opportunities for future research and innovation. This effort includes not only identifying gaps in knowledge but also in supporting institutional background and proposing new avenues to limit the challenges for the next decade. To do such an ambitious task, the Think Tanks count on a group of experts in different cosmovision, backgrounds and levels of knowledge -ranging from practical and tacit expertise to highly academic- that with their participation and insights will incorporate also bottom-up needs, drivers, and bottlenecks throughout the process.

1.2 Objectives

The main objective of this deliverable is the overview of the initial insights prepared by each Think Tank corresponding to each Soil Mission Objective, SMO. Two added TTs are included incorporating two highlighted elements. Those are the nature conservation of soil biodiversity and the climate smart agriculture. The latter is related to EJP SOIL project -related to the National Hub consultations- and its incorporation has another timing due to its nature; implying in this version their insights are not incorporated yet.

SOLO project has an ultimate goal, to provide a final actionable trans-disciplinary roadmap by 2027 is the consecution of several roadmaps at different scales (per TT and per regional node). The project understands the consecution of the roadmap as an iterative process throughout SOLO lifespan.

During the first year of the SOLO project, the Think Tanks were created, a common structure and guideline was provided (D2.1 and D2.2), and initial discussions took place in different formats in 2023. The main objective of this document is to provide a synthesis of what each TT has been developed. Taking into consideration this year has been the foundation of the TT, this deliverable constitutes the first stone on the work carried out per TT. The TTs are groups of experts leaded by consortium partners, but the efforts are constructed thanks to all the stakeholders involved into the process (see 1.2.1 section for further clarifications).

All the insights provided here are opening a process of four years, in which every year corresponds to an interaction of several factors at both the internal and external part of the project. On the former we include the interaction among TTs, with Regional Nodes, with the drivers, with the KPIs developed, and the outcomes from a global synthesis from WP4. The latter implies to open the insights developed per TT to the broad public. This is performed by the Soil Network of Knowledge, SNK, in an ARPHA repository that allows us to open any draft to a global discussion.

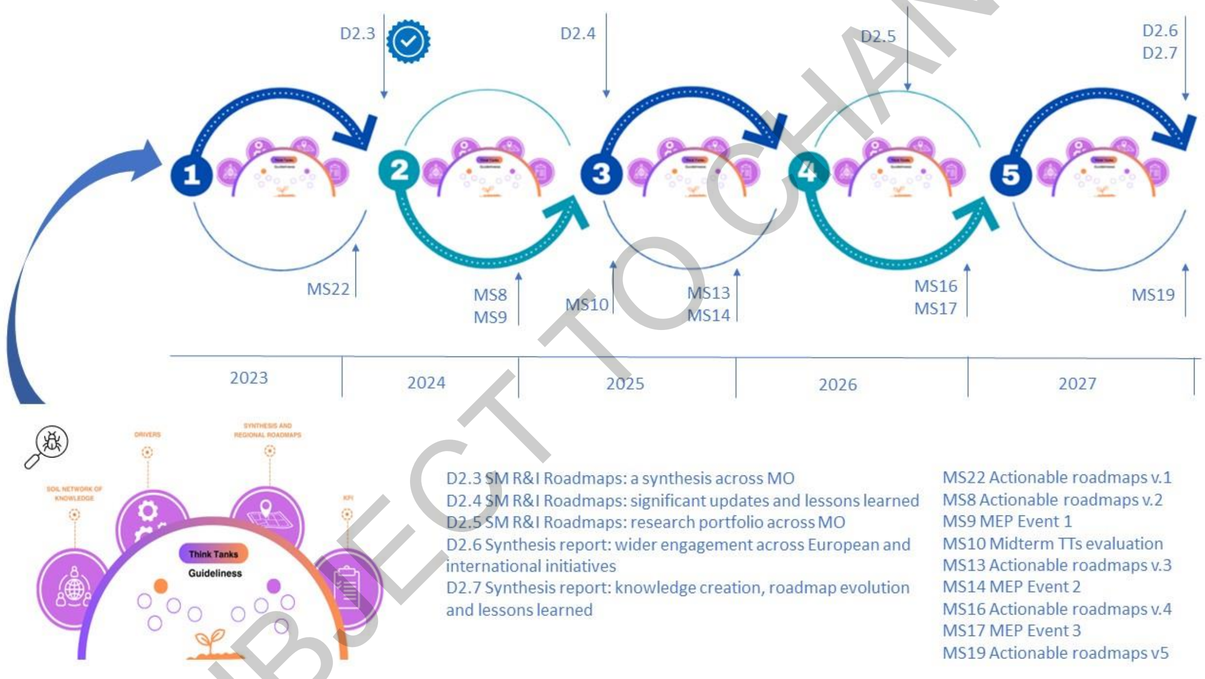

Figure 2: Iterative process and outputs from the TTs in SOLO lifespan; being nourished by the year before and nourishing the incoming year. At the bottom left the two-ways interaction of TTs with the different elements of the project (the network of knowledge, soil health drivers, regional roadmaps and KPIs) and the main yearly outputs; in the middle-bottom the Deliverables and in the right the Milestones definitions are listed for the Soil Mission Research & Innovation (SM R&I) Roadmaps.

The Think Tanks have started with a common structure for the roadmaps, the defining actions, bottlenecks linked those with the GAPs definition (defined in section 4 on D2.1). Prior to the roadmap definition, each TT defined their own characteristics (main definitions on what they are specifically targeting and how they are proceeding on that) and a state-of-the-play of what is considered key in that regard. This deliverable synthetises these first definitions and main insights from each TT. That includes how each TT was defined, constituted and their state of art (considered here also as state-of-play). The main knowledge GAPs complied and discussed among the TTs are also incorporated into this deliverable.

Therefore, the document is structured as follows. Section 1 is an overview of the process developed by the TT and its evolvement in these first 15 months of the project. Section 2 provides an initial state-of-the-play section in which each TT describes the main points in which every Mission Objective is currently being addressed in Europe. Section 3 includes all the GAPs highlighted per each TT and section 4 includes the next steps for the TT to go deeper into them and complement them/ when necessary.

1.2.1 Evolvement of the TTs

SOLO backbone is the Think Tanks to transdisciplinary deliver actionable roadmaps for future soil-related research activities in the EU, which contribute to achieving the objectives of the EU Soil Mission. In this period the constitution of the Think Tanks, seeking for stakeholders' experts on the different SMO, was crucial to ensure transdisciplinarity. Therefore, the main efforts were placed to build on the Think Tanks experts covering a wider range as possible, in an effort to gather their diverse perspectives, expertise and knowledges; paying attention and encouraging their engagement from different spheres[1], backgrounds, ages, gender, places and nationalities in regard to different dimensions of Soil Health.

Active collaboration is what was mostly desired from the potential stakeholders in a transdisciplinary manner as described in D2.1 and D2.2. That is why, from the outset to build on trust and transparency was considered key. In that sense, when first contacting with the potential stakeholders for the different TT, a list of options was given, ranging from strong collaboration to small and punctual involvement through surveys and revisions. Namely, from the outset the implications, expectations, and motivations for the 5-years involvement were shared and agreed. It served us as a baseline for the consecution of the TT, understanding them as an "onion layers system" in which the *key stakeholders*, the ones really involved in a stronger collaborative manner are at the core of the onion, passing by the interaction with soil week events, regional nodes and other project WPs (see Figure 2 for more details) meanwhile at the latest onion layers we can find stakeholders involved into the review of the documents uploaded in the ARPHA repository.

Additionally, the project builds and connects all the stakeholders involved providing interaction among the TTs. In this initial phase, monthly meetings were carried out in which strengths and barriers were shared among TT leaders. Sharing documents and processes helped to better understand the similitudes and differences among them, at the same time building on community knowledge. There are several examples and layers of that collaboration and sharing process among TTs. For example, the Erosion TT especially categorise types of knowledge gaps and therefore the experts. The involvement and interaction of those different expert groups was considered a must as a transdisciplinary project at the different steps followed. Most of the other TTs mirrored the process and include, at least the type of knowledge gaps into their internal process. This category is as follows:

[1] *defined in the quintuple helix: research, governance, civil society, businesses and environmental organizations.*

1. **Knowledge** Gaps in existing European Research and Innovation priorities related to soil erosion, inclusive of Social Sciences' and Humanities' contributions.
2. **Knowledge Transfer** Gaps: This dimension concentrates on the deficient links between available knowledge and its adoption by stakeholders and the broader civil society. We emphasise understanding and addressing the gaps hindering the effective transfer of knowledge to key audiences.
3. **Knowledge Implementation** Gaps: This aspect delves into the challenges linked to the practical application of existing and transferred knowledge. This involves navigating issues such as the adaptation of European-level instruments within national or regional contexts, as well as fragmented advisory services. The emphasis is on exploring obstacles to the actual implementation of knowledge in the real-world.

The actions every Think Tank was committed to during 2023 were i) the initial screening process of key stakeholders, ii) the invitation of the potential key stakeholders (with the considerations described above), iii) the inclusion of the key stakeholders following their level of engagement, iv) at least one online meeting (many TTs had two or more online meetings from June to November), v) the initial draft of a roadmap following the template provided in June 2023 (D2.1) and shared in November, vi) the initial draft of the TT state of the art also shared in November, vii) a face-to-face meeting of three days were the TT discussed in a vibrant and participatory manner all the details of the internal governance of the TT, the initial roadmaps, the interaction among TTs, and the next steps and potential way forward needed to achieve SOLO main goal.

Starting 2024, the TTs have been updating the fruitful discussions and insights of the meetings into the draft related to the state of the art, and the main initial GAPs included into the roadmaps. Additionally, the scoping documents drafts have been updated and are under review by a public audience through the ARPHA; as the last layer of the onion. The results of this process and the insights provided by other WPs and planned meetings will provide the second version of the roadmap (Figure 2).

The commitment to transdisciplinarity and active collaboration of the TTs was effort and time consuming but absolutely necessary. It is essential to highlight that this is a journey, an open process by design, meaning the stakeholders screening and involvement is always open and the dynamics of the TTs may change and grow focusing on the SMO consecution at a time incorporating the transversal objectives of the mission. The initial results of this process are incorporated into this document focused on the state of the art and prior knowledge gaps identified per TT as a process outcome for the last 15 months (as described in this section). SOLO ambitious venture goes beyond document drafts, revisions and reviews, it unifies those whom in a different manner contributes and build community promoting Soil Health, and why not, passion, on soil health and dream of a more just and sustainable future.

2 State-of-the-Play for all the Mission Objectives and Think Tanks.

2.1 Reduce Land Degradation

2.1.1 Introduction

One of the major processes that affect soil and land in general at a global level is Land Degradation. Land degradation is a major global environmental concern with severe consequences, including the potential for mass species extinction, significant losses in biodiversity and ecosystem services, and harm to the well-being of at least 3.2 billion people worldwide (*Brooks et al. 2006*, *Cardinale et al. 2012*, *Haddad et al. 2015*, *UNDP 2019*, *Li et al. 2021*). Furthermore, a substantial consensus within reports and assessments indicates that a significant segment of the Earth's land surface confronts degradation, estimated at between 20% and 40% of the total global land area (*UN Convention to Combat Desertification 2019*, *UN Economic and Social Council 2019*, *United Nations Convention to Combat Desertification 2022*). Moreover, according to *Wischnewski (2015)*, 169 out of 194 countries participating in the United Nations Convention to Combat Desertification (UNCCD) are affected by Land Degradation.

Specific concerns related to land degradation are also prominent within the European Union (EU). Data drawn from all EU Member States, as outlined in the Soil Mission Implementation Plan (*European Comission 2019a*), highlight several alarming issues. Notably, it reveals that 83% of agricultural soils within the EU contain residual pesticides. In addition, a substantial number of potentially contaminated sites, amounting to 2.8 million, exist, with a mere 65,000 having undergone remediation efforts by 2018 (*European Comission 2019a*). Within the EU, issues related to erosion by water, compaction, and soil sealing and excavation also persist. Approximately 24% of EU land is marked by unsustainable water erosion rates, 23% experiences compaction, and a staggering 520 million tonnes of soil are excavated and treated as waste, despite the majority of it not being contaminated (*European Comission 2019a*).

Furthermore, the Soil Mission Implementation Plan (*European Comission 2019a*) underscores the pressing imperative to address land degradation and desertification[2]. This urgency is reflected in the inclusion of the 'Reduction of land degradation relating to desertification' within the Specific Objectives (more precisely, SO1) of the Mission.

It is noteworthy that SO1 is intricately linked to the Mission's Target 1.1, which aims to 'Halt desertification to help achieve land degradation neutrality and initiate restoration'—a commitment aligned with Sustainable Development Goal (SDG) target 15.3 (Combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation neutral world), which works as a catalyst for the attainment of other SDGs according to the UNCCD (*European Comission 2006*, *IPCC (Inter-Governmental Panel on Climate Change) 2001*). Additionally, SO1 encompasses all eight soil health indicators outlined in the Soil Mission Implementation Plan (*European Comission 2019a*). This strategic integration emphasizes the comprehensive approach the Soil Mission is adopting to effectively combat land degradation and contribute to European and global sustainability efforts.

It is important to highlight that the Global Land Outlook report (*United Nations Convention to Combat Desertification 2022*) warns that without immediate actions, the problem of land degradation will persist and escalate. By the year 2050, if the current rates continue, an expanse equivalent in size to South America is projected to experience degradation (*United Nations Convention to Combat Desertification 2022*). This emphasizes the pressing need to address land degradation urgently to avert further environmental deterioration.

Mitigating land degradation necessitates a comprehensive approach that encompasses sustainable land management practices, soil conservation, reforestation efforts, and initiatives aimed at curbing pollution and contamination. International collaboration, as exemplified by the UNCCD, holds significant importance in tackling this global challenge and safeguarding the

[2] Particularly as 25% of land in Eastern, Southern, and Central Europe faces the risk of desertification [10].

integrity of our land resources for the benefit of future generations. The upcoming decades will be decisive in shaping and implementing a fresh and transformative EU and global strategy for land management and conservation.

Considering the above, the Land Degradation Think Tank main objectives are to:

- Identify knowledge gaps and novel venues in all related fields (research, policy, social awareness, etc.) and highlight the needs and priorities that will lead to the LDN EU by 2050.
- Work along with the EU Soil Mission by supporting its specific objectives relevant to "Reducing Land Degradation" and to the other TT's.
- Co-develop the Mission's comprehensive roadmap for Land Degradation Reduction, Restoration, Prevention & Sustainable Management that will intend to facilitate knowledge exchange and establish a strong connection to current and future EU and international soil health projects focusing on Land Degradation.
- Implement an effective multi-actor and systemic approach to accomplish the aforementioned goals.

2.1.2 State-of-the-art

Several methods, approaches and datasets are being developed and used to assess the status of the complex and dynamic processes of LD. More precisely, examples of datasets that provide information about LD components are the Soil Organic Carbon[3] and Salt Affected Soils[4] datasets of the Food and Agriculture Organization of the United Nations (FAO), the Soil Erosion by Water[5] (based on the RUSLE model) and the Soil Erosion by Wind[6] (based on the RWEQ model) datasets of the Joint Research Centre – European Soil Data Centre datasets as well as several datasets that refer to burnt/ flooded areas, geological formations etc.

Furthermore, over the last decade, various concepts and approaches have emerged for establishing schemes regarding Land Degradation monitoring and assessments. Essential examples of these concepts and approaches are the usage of biophysical (e.g. plant cover and agricultural productivity trends, net primary productivity, soil erosion etc.) (*European Commission 2006b*), environmental (*ClientEarth 2022*) and/or socio-economic factors (e.g. poverty, migration and population density) (*Akhtar-Schuster et al. 2017*, *European Commission 2020a*, *European Commission 2020b*) as well as the utilization of long-term satellite observations (e.g. Sentinel-2 optical satellite constellation) (*ClientEarth 2022*, *European Commission 2020a*, *United Nations 2023*) which provides a practical way of generating a monitoring system that can derive cost effective and widely applicable indicators of Land Degradation. In addition, Land Degradation is also assessed by fine-scale field-based and modelling techniques, Geographic Information Systems (GIS), informatics (Machine-Learning and Artificial Intelligence models), time-series and residual trends (*European Commission 2020a*, *European Commission 2020b*, *United Nations*

[3] The dataset can be found at: http://54.229.242.119/GSOCmap/

[4] The dataset can be found at: http://54.229.242.119/GloSIS/

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

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

2023, *European Commission 2019b*, *European Commission 2021*, *European Commission 2021b*) etc.

Lastly, to objectively assess the research landscape of land degradation, Xie et al, 2020 (*European Commission 2021c*) employed bibliometrix and biblioshiny software packages to perform data mining and quantitative analysis on research papers within the field of land degradation from 1990 to 2019 in the Web of Science core collection database. Their findings reveal the following (*European Commission 2021c*):

1. Over the past two decades, there has been a notable increase in the number of research papers addressing land degradation. This growth can be categorized into four stages based on publication volume: an initial low-production exploration phase, a developmental sprout period, an expansion and promotion phase, and a subsequent high-yield active period.

2. Land degradation research spans across 93 countries and regions. The top five nations in terms of research output are China, the United States, the United Kingdom, Germany, and Australia. Among these, China, the United States, and the United Kingdom play significant roles in international collaboration in the field of land degradation, although overall cooperation between countries is not highly intensive.

3. Key topics and high-frequency keywords in recent years within the realm of land degradation encompass terms like "degradation," "desertification," "remote sensing," "soil erosion," and "soil degradation."

In conclusion, future research directions in the field of land degradation should encompass topics such as the processes, mechanisms, and impacts of land degradation, including the economics of Land Degradation as a reason why degradation continues to take place, the application of new technologies and monitoring methods, theoretical advancements, ecological restoration methods and models, interdisciplinary system research, the establishment of policy frameworks for sustainable land management, and intensified exploration of land resource engineering (*European Commission 2021c*).

2.2 Conserve and increase soil organic carbon stocks

2.2.1 Introduction

The EU mission: a soil deal for Europe, defines "conserving soil organic carbon stocks" as one of the 8 mission objectives, addressing the importance of maintaining, or in many situations increasing the soil organic carbon stocks. In cropland soils, the soil organic carbon (SOC) stock is often declining, and vulnerable to further losses due to intensive management and climate change. To combine global climate change mitigation and adaptation, through soil organic carbon sequestration while at the same time enhancing food security is challenging, and further research is required.

There is overwhelming evidence that increasing soil organic carbon stock in agricultural soils may help sustain or even improve biological, physical, and chemical soil properties, with benefits for soil organisms, root growth, as well as a range of other functions of soils important for many ecosystem services. Recent findings address microbial carbon use efficiency (CUE) to be the most important mechanism determining SOC storage and spatial variation, more than the total carbon input, it's decomposition and vertical transport, (Tao et al., 2023). Conserving SOC in soils may support climate change adaptation and resilience to adverse weather conditions (Moinet et al., 2022; Powlson and Galdos, 2023).

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 gras and heath lands) and documentation on consequences of land use changes, impacts of urbanisation and new technologies on soil properties and soil organic carbon stores.

This think tank's main objective is to deliver an overall roadmap targeting the soil mission objective "conserving and increasing soil organic carbon stocks". The objective addresses the importance of maintaining, or in many situations increasing the soil organic carbon stocks.

The think tank will specifically address the impact of:

- Forestry management
- Agronomic and land use managements
- Climate change and adaptation technologies
- Biodiversity and soil health
- Urbanization and circular economy
- Education and awareness raising
- Soil carbon measuring and monitoring
- EU-footprints on SOC-stocks outside EU

By involving farmers, politicians, city planners, outreach services, other key stakeholders and relevant soil network partners in a dynamic and transdisciplinary cluster, a roadmap is being developed by identifying knowledge gaps, bottlenecks, and novel technological innovations to implement the soil organic carbon mission objective.

Coming soil week events targeting a range of soil-use actors from farmers, outreach- and advisory services, to students and policy makers, will involve more stakeholders and soil network partners in further development and revision of documents made available by SNK.

2.2.2 State-of-the-art

More carbon resides in the soil than in the atmosphere and all plant life combined. However, soils can act either as a carbon source or sink, and currently represent a net source of greenhouse gas emissions in the EU (European Environmental Agency (EEA, 2022). Thus, soil management poses a risk to achieving European Union climate targets if not addressed appropriately. EU member states reported a total loss of 108 Mt CO_2 from cultivation and drainage of 17.8 Mha of organic soils in the year 2019, whereas 44 Mt CO_2 were removed from the atmosphere by 387.6 Mha mineral soils (EEA, 2022). In Europe, peat soils contains the highest carbon stocks (Batjes, 2002; De Vos et al., 2015), but it is essential to manage the water level of peat wetlands to maintain their soil carbon stocks (Lloyd, 2006)

The soil mission objective 'Enhance and increase soil organic carbon stocks' aims at identifying actions that can limit the current carbon losses from cultivated soils and preferably reverse it to a rate of 0,1 - 0,4% increase per year (European Commission n.d.). The mission's objectives are relevant not only for supporting the aim to improve soil health by 2030, but also for the member states to become carbon neutral by 2050 (European Commission, n.d.).

In general, changes in soil carbon stocks are slow and management effects will vary depending on climate zones and soil types. In essence is an open dialog and interaction with farmers, forest owners, landowners, extension services, policy makers and other stakeholders of utmost importance for the successful implementation of soil carbon management technologies. Practitioners holds essential knowledge and experience about their own land, and mutual knowledge and practice exchange, will facilitate and stimulate the necessary engagement for innovative technology implementation within the various aspects of soil carbon stocks and improvement of soil health in general.

Forest management

Forestry, forest management and soil carbon stocks are important topics for climate change adaptation. Forest soils store almost half of the total organic carbon in terrestrial ecosystems, and forest management practices can influence the rates of input or release of carbon from soils (Mayer et al., 2020; Mäkipää et al., 2023; Ontl et al., 2020). Forest management can have various objectives, such as timber production, biodiversity conservation, recreation, carbon sequestration, and other ecosystem services. Forest management also affect the SOC stocks. The state of the art in forest management and SOC stocks is a complex and evolving field of research, as there are many factors that influence the interactions between forest management and SOC stocks, such as forest type, soil type, climate, disturbance, time (Ahmed et al., 2012; Jandl et al., 2021) and ultimately the CUE (Qiao et al., 2019; Tao et al., 2023).

Several studies underscore the need for sustainable management practices and innovative solutions to meet the growing demand for timber and forest waste as bioenergy in the context of climate change, and the potential impacts on traditional wood users, forestland uses, and carbon sequestration, with supply responses playing a crucial role in moderating these effects. The demand for wood-based energy is expected to increase, but the carbon impacts of forest bioenergy are uncertain due to optimistic assumptions about forest management (Giuntoli et al., 2020). This is further complicated by the potential effects of climate change and air pollution on forest productivity and carbon sequestration (Matyssek et al., 2012). The removal of forest residues for bioenergy could also have negative consequences on ecosystem services and long-term sustainability (Clark, 2012). The effect of bioenergy demands on timber markets, carbon, and land use is complex and requires further studies.

Agronomic practices

In the context of climate change and food security, soil carbon stocks and quality are influenced by climate, the rate of plant primary production, plant root interaction with soil and soil biology (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). These and other geochemical factors control the soil microbial carbon use efficiency which ultimately is a major determinant for the soil carbon stock (Tao et al., 2023).

The effects of tillage on SOC are not uniform and depend on various factors, such as soil type, climate, crop type, residue management, and duration of tillage (Fornara and Higgins, 2022). For example, a meta-analysis of 446 studies found that NT (no tillage) decreased upland crop yields (wheat and maize) by 5% on average, but increased SOC sequestration by 9.9%. The effects of NT on yield and SOC varied depending on the regulating factors. NT increased yields in relatively arid areas, but reduced yields in more humid areas, whereas SOC was more likely to increase in humid regions. SOC sequestration increased with temperature, but yield losses also increased in warmer regions. The authors suggested that NT combined with crop residue return and crop rotation could enhance SOC sequestration under moist and warm conditions without compromising crop yield (Haddaway et al., 2017).

Crop rotation is another important factor that affects SOC dynamics. Crop rotation is the practice of growing different crops in a sequence on the same field, which can improve soil fertility, pest and disease control, weed suppression, and crop productivity. Crop rotation can also influence SOC by altering the quantity and quality of crop residues, root biomass, and rhizodeposition (the release of organic substances by plant roots into the soil). Different crops have different effects on SOC depending on their growth characteristics, such as C/N ratio, lignin content, root/shoot ratio, and rooting depth. Generally, crops with higher C/N ratio, lignin content, and root biomass tend to increase SOC, while crops with lower C/N ratio, lignin content, and root biomass tend to decrease SOC. For example, a study of 500 agricultural grasslands in the UK found that grasslands with legume-based rotations had lower SOC than grasslands with grass-based rotations, because legumes have lower C/N ratio and lignin content than grasses (Fornara and Higgins, 2022).

Cover crops have many benefits (decreased nitrate leaching over winter, decreased soil erosion compared to bare soil), but their role in increasing SOC may have distinct limitations in many European situations. For instance, in regions of NW Europe with temperate climate, autumn-sown crops are common, which leaves limited scope to include cover crops unless under sown at an early stage in the development of the main crop. A recent review calls into question the often-quoted view that cover crops can increase SOC by about 0.3 tC/ha/yr – see (Chaplot and Smith, 2023). Depending on climatic region and plant species, cover crops may contribute substantially to greenhouse gas emissions over the winter (Guenet et al., 2021; Lugato, Leip and Jones, 2018)

Regenerative agriculture (RA) may not have an exact definition, and the practice varies between regions and farmers and farming systems but generally it includes conservation tillage, crop residue management, and balanced fertilization. These practices in combination have shown to increase soil organic carbon (SOC) stocks (H; and Singh, 2020; Rhodes, 2017). Regenerative agriculture do not only enhance carbon storage but reports also indicate improved soil fertility and crop yields (Rhodes, 2017). Agroecological crop management, particularly reduced or no-tillage and cover crops, can have the potential to further mitigate soil respiration and increase SOC content (Breil et al., 2021).

Another potential solution is conservation agriculture (CA), which is based on three principles: minimal soil disturbance, permanent soil cover, and crop rotation. However, 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 great potential to increase SOC and total N in topsoil layers (Bohoussou et al., 2022).

Agroforestry and intercropping have been found to significantly impact soil organic carbon stocks in Europe. Zuazo (2014) found that forest, shrubland, and grassland in a Mediterranean agroforestry landscape had higher soil organic carbon stocks compared to abandoned farmland. Kay (2019) further 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 and environmentally friendly farming management on soil organic carbon content in European agroecosystems (Francaviglia et al., 2019).

Sustainable food production requires increasing the productivity and efficiency of land, water, and other inputs, while reducing the environmental impact and greenhouse gas emissions of agriculture. Overall, the adoption of recommended agricultural practices, such as reduced tillage, crop rotation, cover crops, including agroecology and intercropping can lead to enhanced SOC storage and restoration of soil quality, and by that strengthen food security.

Climate adaptation

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 are difficult to measure and predict. Two recent approaches to studying climate change adaptation in agriculture are panel data methods and spatial general equilibrium models (Page, Dang and Dalal, 2020).

Biodiversity

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. Already in 1994, Tilman and Downing reported that preservation of biodiversity is essential for the maintenance of stable productivity in ecosystems (Tilman and Downing, 1994). It may be the case that in high clay soils where essential elements are limiting that the best yielding monoculture species may be superior to a mixture of plant species for producing biomass and storing soil carbon. However, there are also a host of what ecologists call niche differences that could also explain why in some cases a higher number of species would yield greater soil carbon. For example, species can differentiate in hot and dry vs cold and wet seasons, exhibit different rooting depths, and produce 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)

Soil health – One health

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). Thus has 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, been a matter of intense research (Georgiou et al., 2022; Liang, Schimel and Jastrow, 2017).

Many lists of indicators for soil quality and soil health include carbon content and microbial respiration together because they are positively correlated. Microbial biomass does provide 'early warning' of slow changes in total SOC (Powlson, Brookes and Christensen, 1987). But biomass is not the easiest method for routine use. Alternatives exists - see Bongiorno et al (2019). As microbial activity and nutrient release increase with increasing carbon content, nutrient mining can occur, counteracting ideas of improving soil health.

Circular bioeconomy

In a sustainable bioeconomy (Hellsmark et al., 2016; Sawatdeenarunat et al., 2016), recycling of nutrients from organic residues is imperative. There is a huge diversity in organic residues depending on their origin and/or the type of process involved in their production. Application of organic residues as soil amendment and fertilizer to agricultural land gives the opportunity of recovering the nutrients, primarily nitrogen and phosphorus, and of potentially improving soil quality by adding organic matter. However, such residues may also increase greenhouse gas production.

Urbanisation

Urbanization is the process of transforming rural areas into urban areas, which can have various effects on food production and soil organic carbon (SOC) stocks. Some loss of agricultural land due to urbanisation seems thus inevitable. Generally, there is a major conflict of interest between urbanisation and the protection of productive soil. High quality soil for agriculture is a non-renewable resource since it takes centuries to build up few centimetres of productive soil. The conversion of agricultural land to urban land is an irreversible process (Amundson et al., 2015), decreasing the land's ability to supply food and other vital ecosystem services (Tan et al., 2009). Historically, urbanization has occurred close to our most productive farmland (Ferrara et al., 2014), and most remaining farmland is located close to urban settlements. Thus, urban sprawl is consuming fertile agricultural land for urban use worldwide (Skog and Steinnes, 2016). How to combine increased food production and soil organic matter conservation with increased urbanization and high pressure on productive agricultural land, i.e., multifunctional land use, is a challenge.

Education and awareness raising

Education and awareness on the importance of SOC management for global benefits, particularly in climate change adaptation and food security is challenging to communicate. Partly because of the several challenges in SOC research its selves. The awareness on the importance of soil health has increased recently though, and in light of this recognition of soil and its importance sustain essential ecosystem services, there is in fact a need to improve fellow citizens, land managers, politicians and policymakers common understanding of SOC dynamics and its central role in soil fertility and carbon storage. This is more important than ever. Many people are generally not aware of the very essential role and value of soil organic carbon, and how their actions can affect it. Therefore, there is a need for education and awareness raising on carbon stocks in soil, and how to increase and protect them (Chenu et al., 2019).

EU footprints of soil carbon outside Europe

The import of food and fibre into Europe has a complex and varied impact on soil organic carbon (SOC) levels in soils outside of Europe. Frank et al (2015) found that changes in SOC stocks depend on management regime and environmental factors, with a potential for carbon sequestration in European cropland. However, this could lead to emissions outside of Europe. To improve our understanding on soil organic carbon (SOC) stock outside Europe, standardized estimation methods, comprehensive data sets, and accurate mapping techniques is needed (Aksoy, Yigini and Montanarella, 2016; Lorenz, Lal and Ehlers, 2019; Lugato et al., 2014; Wiesmeier et al., 2012).

2.3 No net soil sealing and increase the reuse of urban soil

2.3.1 Introduction

The Mission "A Soil Deal for Europe", or EU Soil Mission (EC, 2022a), supports the implementation of the EU Soil Strategy for 2030 (EC, 2021b) by finding solutions to protect and restore soil health. The mission defines eight specific objectives that future research and innovation activities should address. The third specific objective is to achieve *no net soil sealing and increase the reuse of urban soil*. The associated target 3.1 details the twofold aim of: i) increasing urban recycling of land beyond 13%, and ii) switching from 2.4% to no net soil sealing. The implementation plan of the Mission identifies two soil health indicators especially relevant to monitor the progress towards the third specific objective: i) soil structure (including soil bulk density, absence of soil sealing, erosion and water infiltration), and ii) vegetation cover. An additional indicator, landscape heterogeneity, is not explicitly associated with target 3.1 but refers to the issue of connectedness of urban green infrastructure as a fundamental aspect determining biodiversity, water cycle, and soil erosion in urban areas.

The third specific objective of the Soil Mission is linked to several other strategies, goals, and targets of the EU, including those expressed in the Roadmap to a Resource Efficient Europe (EC, 2011a) (especially the target of "no net land take" by 2050), the EU Biodiversity Strategy to 2030 (EC, 2021c), the proposal of a Nature Restoration Law (EC, 2022b), and the EU Action Plan "Towards Zero Pollution for Air, Water and Soil" (EC, 2021a). Achieving no net soil sealing and increasing the reuse of urban soils would also contribute to other EU Missions and related policy areas, such as *Oceans, Seas and Waters* (management of water quality and quantity in urban areas), *Adaptation to Climate Change* (flood mitigation), and *Climate Neutral and Smart Cities* (climate mitigation and resource efficiency). In addition, the specific objective is directly linked to several targets of SDG 11 - Make cities and human settlements inclusive, safe, resilient and sustainable.

2.3.2 State-of-the-art

While the third specific objective of the Soil Mission puts together the issues of soil sealing and urban soil reuse, the two topics are usually addressed in separate ways by different scientific disciplines and stakeholders' groups. For this reason, the following short description of the state-of-the-art -focused on the EU- is divided into two sub-chapters. The Think Tank identified in the perspective promoted by the Soil Mission a potential for innovation, but at the same time acknowledged the existing boundaries between the two communities of experts, and the additional work that this cross-link requires. A key first step is to build a common ground for discussion based on agreed-upon definitions (see Box 1).

Box 1: Definitions

<u>Land take</u> is the conversion of natural and semi-natural land into artificial land (Soil Monitoring Law - Article 3 (EC, 2023a)). Land take is a process often driven by economic development needs, which transforms natural and semi-natural areas (including agricultural and forestry land, gardens and parks) into artificial land development, using soil as a platform for constructions and infrastructure, as a direct source of raw material or as archive for historic patrimony. This transformation may cause the loss, often irreversibly, of the capacity of soils to

provide other ecosystem services (provision of food and biomass, water and nutrients cycling, basis for biodiversity and carbon storage). (Soil Monitoring Law - Preamble (30), (EC, 2023a))

Soil sealing is the loss of soil resources due to the covering of the soil surface with impervious materials, as a result of urban development and infrastructure construction https://esdac.jrc.ec.europa.eu/themes/soil-sealing.

Land recycling is defined as the reuse of abandoned, vacant or underused land for redevelopment (EEA 2021).

Soil reuse involves the repurposing of excavated soil from construction sites, which may be reused on-site or off-site, taking into account its characteristics and ensuring that they are compatible with the new soil application (Hale et al., 2021).

Soil sealing

Despite being among the human activities with the greatest impacts on soil, data on sealing at the European level have been missing 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 (EC, 2011a). The same Soil Mission implementation plan estimates that the area with poor soil health due to soil sealing is probably <1% of EU land but can be as high as 2.5%. These figures are based on the assumption that sealed areas represent around 50% of artificial areas, which cover 4.2% of the EU.

As a consequence of this lack of direct data, soil sealing at the EU level could only be monitored indirectly by looking at changes in artificial areas. Every six years, the European Environment Agency (EEA) reports on changes in artificial areas and net land take over the whole Europe based on Corine Land Cover maps. Available data cover the period between 2000 and 2018, during which artificial surfaces increased by 7.1%. Despite a reduction in the last decade, land take in EU28 between 2012-2018 still amounted to 539 km^2/year, of which 440 km^2/year are net land take (EEA 2019a). Between 2000 and 2018, 78% of land take affected agricultural areas, consuming 0.6% of all arable lands and permanent crops, 0.5% of all pastures and mosaic farmlands, and 0.3% of all grasslands. Critical trends emerged in specific countries, such as Cyprus, the Netherlands, and Albania, which showed the highest rates of land take in the 18-years period (EEA 2019b).

The main drivers of land take during 2000-2018 were industrial and commercial land use, as well as extension of low-density residential areas and construction sites (EEA 2019b). These findings could also give some hints on the main drivers of soil sealing, although the resolution of Corine Land Cover data is not suitable to capture small-scale urbanisation processes. More detailed data on land take and net land take are available at the level of single cities and commuting zones, based on the Urban Atlas database that provides high-resolution land use land cover maps of 788 Functional Urban Areas across Europe (EEA 2023). On the other hand, the fact that this database does not cover the whole territory of the EU limits its application for large scale (national and continental) monitoring.

In 2018, the Copernicus Land Monitoring Service released the first version of the Imperviousness Density (IMD) high-resolution layer. The product captures the spatial distribution and change over time of artificially sealed areas by storing in a raster map at 10m resolution information about the density of impervious areas in each cell, expressed in a range from 0% to 100%. The maps cover the whole EEA-38 area and the United Kingdom, thus providing a homogeneous dataset to assess soil sealing at the EU level. Updated maps are resealed every three years and those currently available cover the period between 2006 and 2018, although resolution and technical details are not fully aligned across the different versions.

Besides soil sealing, the third Soil Mission specific objective also addresses the increase of land recycling activities. The term “land recycling” refers to one of the indicators developed by the EEA to monitor specific processes linked to land take and is defined as the reuse of abandoned, vacant or underused land for redevelopment. The land recycling indicator includes three components: “green recycling”, “grey recycling”, and “densification” which were assessed for the first time by the EEA in 2018 based on Urban Atlas data (EEA 2021).

The figure of 13% identified in the Soil Mission as the limit to exceed refers to the assessment carried out for the period 2006-2012, when land recycling accounted for only 13% of the total land consumption in European Functional Urban Areas. However, values above 40% were recorded in Finland and Malta, and single Functional Urban Areas (e.g., Belfast - UK, Nice - FR, and Wiesbaden - DE) showed rates above 75%. Densification, i.e., land development within existing urban areas that makes maximum use of the existing infrastructure, accounted for the largest proportion of land recycling (9 % of total land consumption). Grey recycling, i.e., the internal conversions between residential and/or non-residential 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, was a marginal process in all countries and, on average, accounted for only 0.2 % of total land consumption. The monitoring of these indicators by the EEA was discontinued, so more recent figures are not available.

The proposal of a Soil Monitoring Law includes a mandatory monitoring of land take and soil sealing by Member States, to be conducted according to a common monitoring framework defining indicators and minimum methodological criteria. The indicators defined by the Soil Monitoring Law are total artificial land (km^2 and % of Member State surface); land take, reverse land take, and net land take (average per year, in km^2 and % of Member State surface); soil sealing (total km^2 and % of Member State surface). Member States may also measure optional indicators such as: land fragmentation; land recycling rate; land taken for commercial activities, logistic hubs, renewable energies, surfaces such as airports, roads, mines; and consequences of land take such as quantification of loss of ecosystem services and change in floods intensity. The values of soil sealing, and land take indicators should be updated at least every year.

<u>Urban soil reuse</u>

The third specific objective of the Soil Mission also addresses the reuse of urban soils, although no specific target has been set for this part of the objective. In most countries, soils excavated from construction sites are currently considered as waste and disposed on in landfills, which makes them the biggest source of waste in the EU (more than 520 million tonnes only in 2018). 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., Belgium, France, UK).

Indeed, the legal framework around excavated soils and their potential reuse is very different across Member States. In some countries, reuse is encouraged and even enforced for certain soils of high agricultural value (as it is the case of the “national reserves of agricultural soils” in Portugal). 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, only on-site and within a reasonable period of time). Often, additional permits or licences are required, which impose a burden on reuse activities.

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). 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. The current level of knowledge on urban soils is generally poor, also due to the high spatial variability of their properties. 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 places in Germany) and even at the national level (e.g., BDSolU in France).

2.4 Soil Pollution and Restoration

2.4.1 Introduction

Soils, largely hidden from our field of view, some of the protection needs have been unjustifiably overlooked in EU and many national legislations, being treated as inferior to air, water and marine environments. This is the case, for example, for soil biodiversity and diffuse soil pollution. Soils are estimated to harbour about 59% of Earth’s species and possibly more. For example, 90% of fungi, 85% of plants and 50% of bacteria are living in soils (Anthony et al., 2023), and provide the basis for healthy ecosystems and human health (EC, 2023). Healthy soils provide a wide variety of ecosystem services, which are also central to human health, such as biodiversity, nutrient cycling, sustainable plant production, natural pest control, good water quality, water retention, carbon storage and erosion management (GIZ, 2022). Soils are characterised by highly complex processes and interactions, of which many still need to be further explored.

Soil pollution and restoration are, due to their strong linkages to environment, nature, biodiversity, ecosystem functioning, agriculture, human and animal health, water and climate, relevant and connected to a wide framework of EU policies and legislations. (EC, 2023) Specific EU legislation on soils has been lacking for many years.[7] As part of the European Green Deal (europa.eu) and the Biodiversity strategy for 2030 (europa.eu), an EU Soil Strategy for 2030 was published in 2021, setting out a framework and measures for the protection, restoration and sustainable use of EU Soils. A linked policy process for the development of a Soil Law proposal was initiated, leading to the publication of the proposal for an ‘EU Directive on Soil Monitoring and Resilience’ (‘Soil Monitoring Law’, SML) by the European Commission (EC) on 5th of July 2023. There are several EU policy documents and legislation that are directly related to the soil policy framework and mentioned as relevant in reaching the main goals. At the same time, negotiations are ongoing regarding the proposal of the European Commission for an EU Regulation to replace the current

[7] 2006 proposal on Soil (failed)

Directive on Sustainable Use of Pesticides. This proposal aims to lead to effective pesticide reductions and implementation of integrated pest management, which haven't taken place under the current Directive.

The two main guiding documents setting the policy frameworks for soil and directly addressing soil pollution are (i) the Implementation Plan of the Soil Mission, which is also an important component of the European Green Deal and (ii) EU Action Plan: 'Towards Zero Pollution for Air, Water and Soil'. These policy documents specify the problem areas regarding soil health, (polluting economic sectors/activities and polluting agents) and identify targets, based on assessments of the state of the art regarding soil health, identified needs and feasibility of reaching specific goals. One of the outcomes of the implementation of them is the SML proposal. The aim of the SML proposal, published by the EC and currently under negotiation, is to be a cornerstone in reaching the objectives of the EU Soil Strategy for 2030 and the Soil Mission. The SML proposal is much needed and widely welcomed, however, was also criticised by scientists, civil society and drinking water companies (Wageningen University, 2023, EEB, 2023, EurEau, 2023) regarding notable shortcomings. Since it does not address all goals and targets identified in the policy documents, an improvement of the proposal and/or further legislative proposals are needed in order to reach healthy soils by 2050. The lack of clear rules and objectives, and the lack of focus on soil biodiversity and diffuse pollution, have been identified as essential shortcomings of the proposal by the scientific community (EEB, 2023).

The current PRTT used these documents and problem areas described in these documents as a starting point to identify the state-of-the-arts and knowledge gaps, and to provide input for roadmap co-development. The PRTT will focus on soil pollution, soil restoration and remediation, while also taking into account the impact on and of soil pollution regarding connected systems such as water bodies (groundwater, surface water) and air, (air or water born pollution or pollution through leaching and volatilization processes).

The above two strategic documents set specific targets related to "**reducing soil pollution by 2050 to levels no longer considered harmful to health and natural ecosystems".**

As a basis, the PRTT aims to provide a state-of-the-art and an assessment of knowledge gaps, potential (innovative) solutions and actionable research regarding formulated goal's objectives, targets and indicators based on the two main policy documents. Table 1 below indicates the concrete Targets, Baseline and Soil health indicators of the Soil Mission to be achieved by 2030 viewed as capable of contributing to meet the 2050 target: *soil pollution is reduced to levels no longer considered harmful to health and natural ecosystems*. Soil Mission Implementation, p. 16). They were developed based on literature review by the Soil Health and Food Mission Board and the Joint Research Centre (JRC) and the results of which were published as part of the Soil Mission under the section of Support Material. The listed targets and indicators of the Soil Mission do not address all pollution problems identified in the Support Material, or in the Zero Pollution Action Plan as it is demonstrated by the background working documents of the Soil Monitoring Law. While the targets, baselines and indicators are clear reflections on the intention to reduce pollution to a level that is no longer harmful to soil, health and natural ecosystems, there are some aspects that need further clarification to make the targets operational such as baseline year for calculating percentages. In some cases, these negotiations are already taking place outside of the soil mission (e.g. the reduction of the use of pesticides) which demonstrates the interlinkages and intertwined nature of the various policies. PRTT will address the complexity of the issue of soil pollution and reflect on the intertwined nature by highlighting the need for a horizontal approach and integration of soil aspects to all relevant policies. (The need for such an approach is well demonstrated by the Impact Assessment Report accompanying the SLM.) It is important to identify policy areas that are directly linked to soil pollution, because the various policy instruments used in those fields do have an intentional or unintentional impact on pollution that should not be ignored but explored through well-defined research questions.

Table 1: Targets and proposed soil health indicators for the mission objective*: Reduce pollution and enhance restoration in the Soil Mission Implementation Plan*

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

Source: (Soil Mission Implementation, p 16)

2.4.2 State-of-the-art

State-of-the-art in the soil pollution and restoration domain will be further reviewed during the next phase of the project. In this chapter, we lay down the principles and methods to develop a comprehensive overview of the domain and provide a first summary of relevant available knowledge and literature.

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, literature review listed under Reference and the feed-backs from our stakeholders, as explained under domain 3 below. Putting soil health into the centre of the system-approach allows 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. Four main domains were identified as pollution relevant during the scoping process along with the principles that should be integrated into all domains, since they reflect on pollution relevant social and economic aspects.

The four domains:

- **1) Soil pollution:** identification and assessment of the extent of polluting agricultural and non-agricultural human activities and pollutants including (i) inorganic, (ii) organic) (also living organism) based on (i) soil descriptors and (ii) criteria reflecting on soil health
- **2) Effects of pollution:** identification and assessment of 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.
- **3) Stakeholders having impact on pollution or being impacted by pollution:** (i) Negatively affected (directly or indirectly), (ii) Beneficiaries of polluting activities (e.g. polluters and clean-up companies), (iii) Stakeholders influencing decision making (business, civil society), (iv) Decision makers
- **4) Solutions to mitigate Soil Pollution:** identification of availability of and need for both (i) pollution prevention and (ii) restoration and remediation.

The principles for reaching soil pollution reduction targets (2030 and 2050):

(i) Fairness and equality: distribution of and access to natural resources should be fair providing equal opportunity to everyone

(ii) Intergenerational Solidarity: refers to the close relationship between generations and mutual respect

(iii) Precautionary Principle: allows measures to be taken to avoid risk of environmental harm, damage in the face of scientific uncertainty

(iv) Prevention Principle: allows preventive measures to prevent the occurrence of environmental damage

(v) Polluter Pays Principle: costs related to environmental damage should be borne by those caused it**,**

(vi) Public Participation: public can be heard and can affect decisions

(vii) Eco-Economic Decoupling: breaking the links between economic growth and environmental pressure

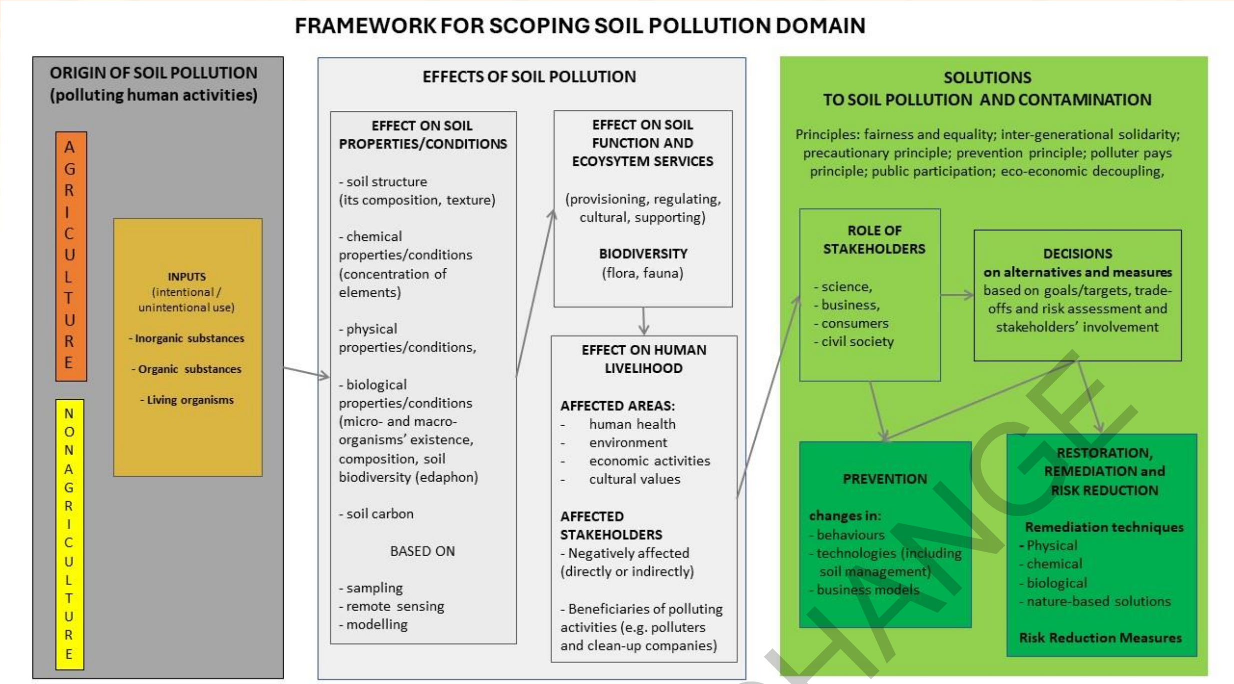

Figure 3: ***Concept overview of System approach to identify interlinkages between domains related to soil pollution/contamination.***

For every domain in Figure 4, linkages with relevant existing and upcoming European policy frameworks and legislation will be assessed. (see Appendix I for example) Policy linkages and means of information gathering will be identified, as well as the needed actions which contribute to different European strategies and missions and their potential feedback to other elements of the domain. Box 2 lists the suggested themes of governance and policy questions that need to be addressed for the analysis of policy linkages. The identified questions are general questions that are used for policy evaluations; thus, it allows easy comparison between policies and policy instruments and measures.

Box 2 Themes of Governance/Policy questions for analysing links between policies.

1. Fitness-for-purpose assessment of pollution and restoration relevant policy frameworks and implementation, identification of bottlenecks (ex post evaluation of policies; whole-of- government approach of rulemaking; outcomes-focused regulation; international regulatory cooperation; assessing the availability of monetary, financial tools along with regulatory tools, impact assessment of implementation and enforcement)

2. Changing behaviour originating from pollution of agriculture and non-agriculture (with focus on behavioural insight of the four main types of stakeholders; the replacement needs in agriculture of the functions of soil additives proved to be polluting; social and economic impacts of the changes)

3. Potentials of technology transformation in reaching targets regarding pollution prevention and restoration (digital technologies, alternative substances and technologies of pollution prevention and

restoration) with considerations given to economic, social and environmental risks, impacts and adverse effects.

4. Evidence based diversification of soil mission 2030 targets among regions (with consideration given to region specificity of biodiversity and soil properties)

5. Research questions identified as governance and policy issues raised in the soil mission and zero pollution documents (e.g. review of hazardous substances for watch list of soil contaminants; review of financial instruments; digital tools (DSS) to help farmers; development of indicators to award “the Green Region of the Year” title).

2.5 Soil Erosion

Soil erosion impacts most of the ecosystem services provided by soils, which is the base of the EU soil strategy for the definition of healthy soils. Soil erosion is the detachment and transport of slope-forming materials by erosive agents, including rainfall, runoff, wind, tillage and co-extraction on root crops and land-based machinery (Rickson, 2023). In many circumstances, soil erosion largely surpasses the soil formation rate. Soil erosion acts on the surface and removes the most valuable part of the soil horizon, having the highest colloid, organic matter content, the best soil structure, the most intensive soil life and the highest capacity to absorb water and nutrients, and to support life. Therefore, soil erosion is not only the quantity of removed soil mass, but also the loss of soil functions and increased need for inputs to manage agricultural production. Soil loss due to erosion compromises soil functions and can have relevant repercussions in agroecosystems (food production, water regulation, carbon sequestration and biodiversity). Massive soil displacement also accounts for multiple off-site effects, such as sediment concentration in water, therefore hindering aquatic life, water quality or deducing water storage capacities and increasing the risk of flooding upon high rainfall and run-off events. It also leads to higher risks of drought due to its decreased water holding capacity: lower water holding capacity decreases the potential evapotranspiration and the temperature buffering capacity, thus increasing the chance of extreme air conditions, and contributing to climate change.

The monitoring of soil displacement and its impacts are among the greatest challenges involving erosion studies. State-of-the art models grant estimates on the geography of cropland susceptibility to soil erosion at the global scale, including projected climate changes by 2070 (Borrelli et al., 2023), and this top-down approach, based on consistent methodology, can be very informative. However, these models have limitations (Schmaltz et al., 2024), and local measurements are also required - models need validation and they cannot contemplate the complexity of interactions governing the erosion processes, particularly the multi-process modelling approach. Field monitoring is therefore fundamental and should be based on plain and comparable methodologies. Several soil erosion prevention and mitigation measures are recognized, but their adoption among practitioners remains challenging. Financial incentives, raising awareness among farmers, innovative farmers and contractors, as well as good advisory services can revert problematic situations (Prasuhn, 2020). Furthermore, education for soil science is still underrepresented in schools (Charzyński et al., 2022) and among practitioners (Cerdà and Rodrigo-Comino, 2021), and increasing literacy on soil issues, including erosion, is necessary.

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

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

It is acknowledged that we need to engage non-academic stakeholders in the identification of solutions to the problem of soil erosion, in what concerns its prevention and mitigation. Hence the TT is a platform that allows engagement, collaborative thinking and hopefully actions towards prevention and mitigation of soil erosion problems.

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

2.6 Soil Structure

2.6.1 Introduction

The EU mission: a soil deal for Europe, defines “improve soil structure” as one of the 8 mission objectives, addressing the importance to enhance habitat quality for soil biota and crops. Soil structure really makes soil what is: how plants can grow there, how air and water and nutrients can move and how it supports the ecosystems services of the soil. The importance of soil structure for many vital processes in soil cannot be ignored as influences both water and nutrient flow, provides aeration to plants and microbes, and helps to resist soil erosion and compaction, and is therefore linked to plant growth.

Intensification of land management is a key driver of soil structural deterioration. Intensive tillage is related to reduced aggregate stability and increased risk for surface sealing and erosion. Similarly, 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. These changes in soil pore system affect water and gas movement in soil and therefore also the living environment of soil biota and plant roots. When changes in soil structure and pore system lead to reduced soil productivity, the input of C through decaying plant materials and root exudates is also reduced leading to decreasing OC content in soil. And lower SOC content is related to lower aggregate stability thus enhancing further the risk for structural deterioration. Regenerative agriculture practices (e.g., holistic grazing, catch crop, cover crop and crop rotation among others) provide an option for the intensive management’s practises. Furthermore, 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. Draught has been shown to decrease carbon accumulation to soils. 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.

2.6.2 State-of-the-art

Soil is healthy when it is in good chemical, biological and physical condition and can continuously provide as many ecosystem services (such as safe, nutritious and sufficient food, biomass, clean water, nutrients cycling, carbon storage and a habitat for biodiversity) as possible. How can we then define what us a good soil structure? One of the most important indicators is how soil structure is connected to the soil water retention and gas exchange. Water retention is responsible for life on Earth as we know it. It allows for a huge air-water interface which permits aquatic aerobic activity to proceed under a range of environmental conditions. This activity underpins many global biogeochemical cycles. While we can destroy soil structure with, for example intensive and wrongly timed soil tillage and forest management practices and excessive handling of soil but we can also preserve soil structure. But can we improve/regenerate destroyed soil structure? The growing interest on reduced tillage and carbon farming have potential to improve aggregate structure but improving the growth conditions of roots and enabling proper water and gas movement deeper in the soil would require loosening the soil structure at least down to the desired root penetration depth. No-till management known to improve soil aggregate stability may, depending on climate and soi type, enhance soil compaction and therefore slowly lead to lower productivity. On the other hand, reduced disturbance of soil improves the living conditions of soil fauna and therefore may have positive effect on soil macroporosity. Thus, need information on soil specific management options in different climatic conditions, soil types and land-use systems to improve and functionality of soil structure.

2.7 Reduce the EU global footprint on Soils.

2.7.1 Introduction

This Think Tank focuses on specific objective 7 of the European soil mission: to reduce the EU global footprint on soils. Within this specific objective, two main objectives have been defined, according to the Soil Mission Implementation Plan:
T 7.1: Establish the EU's global soil footprint in line with international standards
T 7.2: The impact of EU's food, timber and biomass imports on land degradation elsewhere is significantly reduced without creating trade-offs

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

This specific mission objective adds the international dimension to the other mission objectives, which are almost entirely focused on improving soil health and soil functioning in the European Union. As stated in the Mission Implementation Plan, soil health is crucial for three UN conventions (UNCBD, UNCCD, UNFCCC), as well as for the Sustainable Development Goals (SDGs). Yet, the soil health concept should be aligned globally, reducing also the soil footprint outside the EU from food, biomass and timber imports (as stated later, we do not agree with this strong focus on biomass solely). In the soil mission implementation plan, following international dimension is already strongly highlighted.

In Africa, the soil mission aims to collaborate through the FNSSA partnership, part of the EU-Africa Union High-Level Policy Dialogue. This partnership focuses on soil health for sustainable food systems. Projects like Soils4Africa and LEAP4FNSSA should be used to unify international monitoring approaches, to develop capacities, and to spot investment opportunities in soil health. For countries around the Mediterranean, we highlight the PRIMA partnership, which addresses water and agri-food systems in the Mediterranean, preventing further degradation and restoring damaged lands in the Southern Mediterranean.

In Latin America and the Caribbean, cooperation is meant to be focused under the EU-CELAC partnership, that specifically emphasizes sustainable agriculture and bioeconomy research in line with the EU's Horizon Europe program.

Japan and Canada are also key partners. Japan seeks to align its Moonshot program with the EU's Soil mission, while Canada contributes to designing living labs and seeks further R&I collaboration.

The mission also aims to support collaboration with the FAO, particularly its Global Soil Partnership, benefiting from a harmonized framework for soil data and contributing to the FAO's Global Soil Biodiversity Observatory and initiatives on soil biodiversity conservation.

Finally, the mission states that Member States' involvement in the 4per1000 initiative, launched at COP 21, and aims to establish an International Research Consortium (IRC) on soil and carbon to guide global R&I cooperation. This effort aligns with the Global Research Alliance on Agricultural Greenhouse Gases.

2.7.2 State-of-the-art

The state-of-the-art for mission objective 7, and on achieving its goals, is not straightforward to assess or summarize, especially since, to our knowledge, no current overarching research efforts have been made to begin to quantify the detailed impact of EU activities on soil health and soil functions worldwide.

The Soil deal for Europe acknowledges that even in EU soils, it is difficult to assess an overall status of soil health. A key obstacle to EU-wide quantification of soil health is the lack of systematic and harmonized soil monitoring across member states. Unlike other resources such as water, there is no legal requirement for EU member states to report on soils. This results in varying levels of soil monitoring and hinders the ability to effectively monitor and report on the health of European soils. This is testimony to the formidable task that is ahead for achieving soil mission objective 7, which brings together all other EU-based mission objectives, with all related harmonization and integration issues, into one worldwide perspective.

This does not imply there are no current research studies that have tried to partly attribute the impact of EU policy and actions on soils, or rather land footprint, outside of the EU. We here present some recent efforts that have aimed at identifying emerging trends and technologies that can help in establishing the soil footprint, as well as providing novel perspectives and future directions. We also identify key databases that offer the potential for assessing EU global soil footprint.

Representative papers on establishment of global ecological footprint of the EU-food system

The ecological footprint (EF) of the EU-27 between 2004 and 2014, and how it exceeded regional biocapacity, 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, considering both the demand and supply aspects, including trade and multiple externalities. Vanham et al. (2023) performed a similar approach, to track the land footprint (LF) and water footprint (WF) of food consumption in the EU. The EU LF and WF were estimated at 140-222 Mha yr^{-1} and 569-918 km^3 yr^{-1}, constituting 5-7% of global agricultural LF and 6-10% of global agricultural WF. The study also underlined the importance of a consistent methodology, since numbers actually differed strongly from similar earlier efforts.
Giljum et al (2016) identified priority areas for European resource policies using a similar MRIO-based footprint assessment, presenting a comprehensive assessment of the EU from 1995 to

2011. Again, utilizing MRIO modelling, developed with EXIOBASE (an MRIO database), the study revealed a significant shift in the origin of raw materials, with the share extracted within the EU falling from 68% in 1995 to 35% in 2011. Materials extracted in China equalled the share of EU's own material extraction by 2011.

In 2019, Bruckner et al. performed a global cropland footprint of the EU's non-food bioeconomy. A novel hybrid land flow accounting model, combining LANDFLOW with EXIOBASE, was employed to provide detailed insights into product and country-specific footprint. The study revealed that two-thirds of the cropland required for the EU's non-food biomass consumption is located outside the EU, particularly in China, the US, and Indonesia, Notably, oilseeds for biofuels, detergents, and polymers represent the dominant share (39%) of the EU's non-food cropland demand.

Some key papers on country-specific assessment

Cederberg et al. (2019) focused on the environmental impacts of Swedish food consumption, specifically in relation to agrochemicals, greenhouse gas emissions and land impacts. Equally utilizing the EXIOBASE database, the research calculated novel footprint indicators for pesticides and antimicrobial veterinary medicines. Key findings revealed that a significant share of Sweden's pesticide footprint is embedded in imports, primarily from Europe and Latin America. Kalt et al. (2021) performed an analysis tracing Austria's biomass consumption to source countries, using a physical consumption-based accounting approach, combined with national statistics and process chain modelling. 55% of Austria's total biomass consumption originated from domestic forestry or agriculture, and 30% from neighbouring countries. Products with the largest biomass footprints like beef, pork, milk, cereal products, paper, and wood fuels were primarily sourced from Central Europe. Biomass from non-EU countries accounted for about 8% of Austria's primary biomass footprint.

Habitat loss and agricultural trade

Schwarzmueller and Kastner performed a study that linked agricultural trade to global loss of species. Utilizing FAOSTAT data and the Species Habitat Index (SHI) as a measure of ecosystem intactness, the research covered trade flows between 223 countries over 15 years. It showed agricultural expansion as a major driver of biodiversity loss, especially in South America, Southeast Asia, and Sub-Saharan Africa, also showing that Western Europe, North America, and the Middle East have significant biodiversity footprints outside their borders. Particular attention was paid to soybeans, palm oil, and cocoa.

Overarching conclusion

The state-of-the-art analysis shows that the MRIO approach might be a good starting point for analysing and quantifying key exchange of food, feed and timber exchange between the EU and third countries. A key challenge will lie in relating this 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 key potential examples currently available are summarized below:

www.isric.org
This database provides digitized soil survey information from around the world.

https://www.fao.org/global-soil-partnership/regional-partnerships/en/

The Regional Soil Partnerships (RSPs) link up different national soil entities (soil survey institutions, soil management institutions, soil research institutions and soil scientists working in land resources, climate change and biodiversity institutions/programmes), and could be a good starting point for local data for soil functioning assessment.

https://www.footprintnetwork.org/resources/mrio/
Key database for MRIO modelling

https://data.footprintnetwork.org/#/
This database provides e.g. potential footprints by land type and socio-economic worldwide relations.

Based on the state-of-the-art, it becomes clear why the mission objective 7's first sub-objective is focused on establishing a clear baseline for establishing EU's global soil footprint in line with international standards. Current state-of-the-art has only started performing this exercise at large scale, linking trade exchanges to land use but not to specific ecosystem soil functions. Still, it is clear that, based on current knowledge, it should be possible to already establish key policy actions that can already be taken now, to reduce EU global footprint.

2.8 Soil Literacy

2.8.1 Introduction

Soil is probably the most undervalued natural system. Increasingly urbanised populations often see it just as 'dirt' and as an unlimited natural resource, unaware of its relevance in their daily lives and of its key role in a sustainable and circular bioeconomy. This reflects a lack of emphasis in education on the importance of soil and highlights the need to increase public awareness and societal engagement (EU Soil Strategy, 2021). This overall lack of understanding and appreciation of soils result in a lack of investment (both in terms of education and concrete measures to protect soil) and a general political reluctance to pass laws to preserve and enhance soil conditions (EU Soil Observatory, n.d.).

The success of the Soil Mission depends on action being taken by the whole of society from citizens, government to businesses, researchers and many more at all levels. However, the current lack of soil literacy is indeed a major barrier to achieve any soil health improvements. Therefore, all stakeholders must have access to both general education on soil and targeted training for specialised needs (EU Soil Strategy, 2021). It is equally important to understand that in order to trigger citizen action and involvement, people need more than to receive scientific information about soils. **Connecting soil literacy to people's values, interests, activities, and concerns is key**. While some messages may be widely applicable (e.g. healthy soils underpinning achievement of physical and mental health, beautiful and healthy landscapes, good quality food), action on soil literacy should also be linked with specific and locally relevant concerns and should empower citizens to make a change (EU Soil Mission implementation plan, 2021).

Despite its importance, *no prior work considers the conceptualisation and measurement of soil literacy, as well as its constituent components of attitudes, behaviours and competencies, which allow decision-making to enable good soil health and positive impacts on the environment. Understanding the attitudes, behaviours and competencies that drive individual interactions with soil, including factors that promote or harm soil health, is crucial to inform policy responses that* *aim at facilitating sustainable interactions with soil of the future citizens and farming communities* (Johnson et al., 2022)

Soil literacy in Context of the Soil Mission

The goal of the Soil Mission is to create 100 living labs and lighthouses to lead the transition towards healthy soils by 2030. The **mission's goal** is substantiated by **eight specific objectives**, and each of those has various policy targets. The policy targets for the objective "*Increasing soil literacy in society across Member States*" are:

- T. 8.1: **Awareness of the societal role and value of soil** is increased amongst EU citizens, including in key stakeholder groups, and policymakers.
- T. 8.2: **Soil health is firmly embedded in schools and educational curricula**, to enable citizens' behavioural change towards the adoption of sustainable practices both individually and collectively.
- T 8.3: **Citizen involvement** in soil and land-related issues is improved at all levels
- T 8.4: Practitioners and stakeholders have **access to appropriate information and training** to improve skills and to support the adoption of sustainable land management practices.

Soil literacy is heavily linked to one of the four transversal-operational objectives that create connections between already mentioned 8 specific objectives of the soil mission: "*Engage with the soil user community and society at large*,' which is also one of the mechanisms to address the other seven mission objectives: The activities included in this operational objective are:

- Activity 4.1: **Foster soil education across society**
- Activity 4.2: **Engage with and activate municipalities and regions** to design their own strategies and actions for the protection of soil health.
- Activity 4.3: **Engage with the private sector and consumers** to embed soil health in business practices.
- Activity 4.4: **Strengthen soil health advice and improve access to training** for practitioners in line with Agricultural Knowledge and Innovation Systems (AKIS)
- Activity 4.5: **Create citizen-led soil stewardship.**
- Activity 4.6: **Bring soil closer to citizens' values.**

2.8.2 State-of-the-art

Defining what is soil is a complex matter. Within soil sciences, these definitions have changed over time. Beyond soil sciences, different groups have different understandings of what soils are. The way in which soils come to be known, represented, and understood is diverse. *In different regions, farmers, foresters, government officials, soil scientists, or environmental NGOs know soils in different ways, and attach different meanings to them* (Granjou et al., 2022).

There is also the historic context of how soil science has emerged and developed as a topic seeking relevance within the scientific community and governance spheres over the past one hundred years, which adds another level of complexity to the discussion. *Accounts of the history of soil science usually locate the origins of the discipline around 1900*. *However, beginning in the late 1970s, the links to agricultural practice increasingly became weaker (*new technologies, chemicals, modified plant crops etc.)*, and* ***soil science entered a period of rethinking its self-***

understanding, *often described as a legitimation crisis*. *Soil science has re-articulated its relevance in 5 different ways along the years (Sigl et al., 2022*):

- *Epistemic commitment 1: communicating to policymakers, to find new ways of communicating existing soil science knowledge to policymakers.*
- *Epistemic commitment 2: internationalising soil science knowledge, to create international bodies of soil science knowledge with a broad geographical scope.*
- *Epistemic commitment 3: rethinking soil science research by using boundary concepts, when soil scientists started using concepts like ecosystem services, policy cycle, or soil health to improve communication, interaction, and collaboration beyond traditional soil science.*
- *Epistemic commitment 4: the ecosystem approach in soil-related research, an approach that studies soils as part of broader ecosystems with the aim to understand interactions within and beyond soils.*
- *Epistemic commitment 5: developing regional scenarios for (agricultural) soil management, the goal is to use soil management as a means to tackle societal and environmental problems without losing sight of other soil functions, such as local food production or regional economic functions.*

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* (EU Soil Mission implementation plan, 2021). By doing so, the Soil Mission seeks to establish a strong link between soil literacy and soil health. But here comes the catch: **The complexity around the definition of what is soil is transferred to the definition of what soil health is and therefore, to the concept of soil literacy.**

According to the Proposal for Soil Monitoring and Assessment directive, soil health *means the physical, chemical and biological condition of the soil determining its capacity to function as a vital living system and to provide ecosystem services* (European Commission, 2023). This definition only relates to the functional part of the soils and obscures the different understandings and contexts that offer the big diversity of what soil health may be. In that sense, **the soil literacy Think Tank concluded that there is a need to expand the soil health concept beyond the anthropocentric idea related to ecosystem services and the view of soil as a resource humans can benefit from**. The necessary paradigm shift is then moving from a merely anthropocentric utilitarian approach to value soils to an eco-centric deontological one, which attributes all soils an inherent value.

As mentioned before, soil science has moved from a very local and regional perspective in which the main target of soil literacy were farmers and landowners, to a more global perspective that tries to tackle several environmental and societal challenges, and where it deals with different target audiences. Until relatively recently, there has been a very 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 acted on are the scientists. Awareness of the value or importance of soil already exists amongst different groups, however, is not seen as sufficient by soil scientists, who observe soil degradation and land taking place. **With a change in the target audience comes a change on how to go about soil literacy.**

From all of this, we can conclude that there is not a singular soil health idea to transfer through one soil literacy process. But rather, due to the different viewpoints and management priorities of the target audience, there needs to be a varied and adaptive approach to soil literacy, respectful of multiple perspectives and sources of knowledge.

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 done by soil networks like the Global and European Soil Partnerships on soil awareness and capacity building, including their collection of educational materials and the events they organise. Similarly, European projects such as LOESS, HuMUS, PREPSOIL and NBSOIL and their work in collecting the best policies and practices around soil health, trainings and courses are also relevant to building the basis of knowledge around soil literacy, as relevant are the outcomes of over 20 projects under the EU LIFE programme between 2012 and 2019, see LIFE Soil Ex-Post Study - Final Report (Giandrini, 2023).

Case studies outside of Europe may also serve as examples of soil literacy assessment. For example, the findings from a soil literacy survey of a population of school children in three African countries: Ghana, South Africa and Zimbabwe. The study is summarised below:

- Boosting soil literacy in schools can help improve understanding of soil/human health linkages in Generation Z: The study performed by Johnson et al. in 2022 surveyed 3661 school children aged 13–15 in three African countries, Ghana, South Africa and Zimbabwe, for their 'Attitudes, Behaviours and Competencies' of soil, which they termed 'ABC'. The 'ABC' survey results showed significant soil illiteracy. The survey showed that although students were generally equipped with a good attitude to (overall 52% positive) and behaviour towards soil (overall 60% engagement), they had little competency as to how to improve soil health (overall 23% knowledge). For example, less than 35% of respondents across all countries know that soil is living. And less than 13% of students are aware of the important role of soil in climate change mitigation.

The study is supported by The ABC of Soil Literacy Report from the University of Durham (Johnson, 2020). The report defines soil literacy *as a combination of attitudes, behaviours and competencies required to make sound decisions that promote soil health and ultimately contribute to the maintenance and enhancement of the natural environment.* It also offers approaches to measure its levels, focused on this case in the school children of the three African countries, through their soil literacy toolkit, which includes a survey questionnaire, guidance on how to select samples of the target population, and advice on preparing fieldwork teams.

Potential future directions in soil literacy

Soil literacy should *seek to create 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 concrete 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,* limiting land take *(...)* (Krzywoszynska, 2023). A systemic and holistic view when we are speaking about soils ensures a robust soil literacy, considering the relation between soil and other key areas like e.g. water management, circular economy, biodiversity or human and environmental health.

We need to understand that a certain level of soil knowledge already exists, although this is very unequal among the different groups of actors and decision makers whose actions have direct or indirect impacts on soil health. Soil literacy should build up from this pre-existing knowledge and values around soils and find ways to build up actions which can lead to "healthy soils" in a just and equitable manner. In this sense, *a care network model can play a key role, in which an initial attentiveness to one aspect of soils leads to a further attentiveness to other interconnected aspects. For example, farmers' attentiveness to soil structure can lead to an attentiveness to soil biota, and result in changes to land management practices so that the needs of soil biota are respected. Attentiveness can thus have a transformative effect on human-soil relations, leading, for example, to a questioning of models of land use which neglect the needs of soil organisms* (Krzywoszynska, 2023).

Linked to the previous paragraph, in terms of engagement, the Fifth National Climate Assessment - the US Government's pre-eminent report on climate change impacts, risks, and responses - indicates a series of processes and actions to improve the effectiveness of engagement efforts and accessibility to climate information (Marino et al., 2023). These can also be applied in soil literacy:

1. *Co-produced or co-created research is a promising approach for soil literacy as well. This type of research defines non-scientific individuals as experts within their specific context, integrating community-based and scientific insights and solutions. However, integration can fail if power dynamics, goals, trust, and compensation within research teams and epistemologies are not equitable.*
2. *Establishing clear, measurable objectives with well-defined benchmarks or desired outcomes leads to more effective communication products and processes; bringing key stakeholders into the process at this early stage can improve effectiveness.*
3. *To inform real-world decision-making, information needs to be calibrated to the needs of target audiences; importantly, communicating relevant information sometimes involves translating science into accessible and actionable language, whereas in other cases it involves incorporating diverse forms of knowledge into communications products and efforts.*
4. *Efforts that have been successful in engaging people on climate change across existing ideological and cultural divides generally do so by addressing the things people care about most* (car network model mentioned in previous paragraph).
5. *Including intended target audiences throughout the process of developing communication products both promotes procedural justice and increases the likelihood that such efforts meet shared goals.*
6. *Engagement outcomes also strongly reflect the relationships and levels of trust between intended audiences and messengers. The use of trusted messengers increases acceptance and use of climate change risk information.*
7. *Pervasive uncertainty surrounding climate change continues to be a major challenge to communication* (in our case soil health).

Last but not least, soil literacy should be addressed/considered at multiple scales and differentiate between sectors, disciplines, priorities, and age groups. One example of how this could be accomplished comes from the concept of 'Learning for Sustainability (LfS)' education or Education for Sustainability (ESD). The work is based on the green competence framework from the JRC's GreenComp document, published in 2022. The JRC defines 12 broad competence areas clustered on different knowledge, skills and attitude levels. Merging both competence frameworks with the European Green Deal (Farm to fork strategies etc.), different competence areas were developed, starting from a primitive level of knowledge, skills, and attitudes to more advanced concepts.

If some competence areas can be delineated, a target audience could then be segmented by age, interest, educational background, roles and values e.g. kindergarten, schools, youth (university, experts), public officers etc. The levels can go from basic, students from 3-6 years to more advanced progressive knowledge and skills over the years. The focus would be on creating competence-based and not just content-based curricula and training programmes following a progressive multilevel approach. Nevertheless, beside this medium to long term set of goals, there is currently the urge to foster and promote soi literacy among policymakers and stakeholders whose decisions and actions have already a negative impact on soil health across multiple scales of land planning and governance.

As previously stated, the soil health definition misses some key elements. 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. Taking the approach of centring on these competences is a more promising way.

"*People already have knowledge about soils, but technical knowledge enhances them to make better questions* "(Soil Literacy Think Tank member).

2.9 Nature Conservation of Soil Biodiversity

2.9.1 Introduction

In the past decades, there has been an increasing awareness of the importance of Nature Conservation of Soil Biodiversity. More than 59% of all biodiversity on the planet is comprised of soil living organisms, ranging from microorganisms to vertebrate species (FAO et al., 2020). Soil biodiversity plays a central role in soil health and ecosystem services, as the activities of soil biota support the delivery of various ecosystem services, such as carbon sequestration, nutrient cycling, prevention of soil erosion, and cleaning of air and soil. However, intensive use of soils in e.g. agriculture and forests, as well as e.g. soil sealing in urban environments is putting this important biota at risk. Protecting soil biodiversity will have positive effects on a number of sustainability goals, including water quality and food security (FAO et al., 2020; Köninger et al., 2022). Nevertheless, there is evidence from recent work that current conservation practices do not protect soil biodiversity and its ecosystem functions because the priorities and the decision-making paradigms used for selection of sites for conservation do not include soil biodiversity, associated ecosystem functions, or the value of belowground ecosystems (Zeiss et al., 2022). On the other hand, while biodiversity-friendly management approaches such as agroecology (FAO, 2023) and agroforestry practices (Barrios et al., 2023) are receiving increasing attention for biodiversity conservation, sustainable management, and restoration, studies focused on soil biodiversity and ecosystem functions are still limited. Thus, there is an apparent need for identifying knowledge gaps and actions within research and innovation regarding conservation of soil biodiversity.

Recently, soil health and biodiversity has also gained increasing attention in European policy. The EU goal is to have moved well beyond the current status of having only 30-40% of healthy soils by 2030 and by 2050 all EU soil ecosystems are in healthy condition and are thus more resilient. To reach this goal, the EU has put a great effort in setting legal frameworks and strategies that focus on soi health. These frameworks include e.g. the soil strategy and the proposal for the Soil monitoring and resilience law. Additionally, to protect and restore aboveground and belowground species and habitats the EU has frameworks and strategies, e.g. the EU biodiversity strategy for 2030 and the upcoming Commission proposal for a Nature Restoration and resilience Law.

The EU Soil Mission "A Soil Deal for Europe" has at its centre the protection and restoration of degraded soils across Europe. Soil Biodiversity protection and restoration are integral to many of the Soil Mission's eight objectives, which are to:

1. reduce desertification.
2. conserve soil organic carbon stocks.
3. stop soil sealing and increase re-use of urban soils.
4. reduce soil pollution and enhance restoration.
5. prevent erosion.
6. improve soil structure to enhance soil biodiversity.
7. reduce the EU global footprint on soils.
8. improve soil literacy in society.

The SOLO project has also identified the topic of Nature Conservation of Soil Biodiversity as key to the achievement of the Soil Mission in research and innovation. This Think Tank (TT) does so through support to the Soil Mission research and innovation agenda, as well as the soil strategy and the EU biodiversity strategy. The integrative nature of soil biodiversity conservation across the mission objectives is a key feature as soil biodiversity is the basis of functions and ecosystem services.

2.9.2 State-of-the-art

Soil biodiversity is defined by FAO et al. (2020) "as the variety of life belowground, from genes and species to the communities they form, as well as the ecological complexes to which they contribute and to which they belong, from soil micro-habitats to landscapes". To paraphrase Orgiazzi (2022), this, ideally, includes all organisms whose interface with soils is key to their life histories and would be significantly impacted without soil. This is a challenge in research on soil biodiversity as the information of taxa can be on very different levels, due to the minimum funding for the taxonomic and natural history knowledge of the soil organismal groups.

Different aspects of nature conservation methodologies for biodiversity?

In conservation theory and practice, biodiversity can be maintained and protected through two general conservation approaches: integrating conservation in use and management of land and protected areas/off-setting of land for conservation. Methods employed may differ among different land use perspectives.

Protected areas

The Convention on Biological Diversity (CBD) definition of protected area is: "A geographically defined area, which is designated or regulated and managed to achieve specific conservation objectives". These areas are chosen for conservation for varying desired outcomes, both ecological and cultural. The IUCN categorises protected areas depending on the level of protection (see Box 1).

BOX 1: The IUCN categorises of protected areas (Lausche 2011):

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

This current system of categorising protected areas continues to be utilised even though these often take management and not biodiversity outcomes (Boitani et al., 2008) especially soil biodiversity conservation (Zeiss et al., 2022), into account. Zeiss et al. examined soil biodiversity and ecosystem services across nature conservation areas and non-conserved areas across Germany and found that, while conserved areas are assumed to have positive effects on non-target ecosystems, these conservation measures do not positively influence soil biodiversity or show benefit regarding associated ecosystem functions. In evaluating the aims in selecting these sites, multiple reasons were found for the lack of observed effect. Firstly, there is a lack of emphasis on site selection for conservation based on the value of soil biodiversity and associated ecosystem services as evidenced by language used in selection justifications. Secondly, Zeiss et al. found an emphasis on threats to chemical and physical properties of soil in the selection language instead of emphasis on the value of the belowground ecosystems and the functions that influence abiotic factors.

Integration of conservation into Sustainable Use

Protected areas have long been the most important tools in conservation. However, Hummel et al. (2019) mentions that with increased focus on ecosystem services and human well-being the focus is changing from protection of (threatened) species towards e.g. sustainable use. 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" (EC, 1993)

Examples of integration of conservation are e.g. extensive forest management, agro-ecological intensification, agroforestry, and dehesas/montados. The EU Common Agricultural Policy (CAP) provides several suggestions to protect soil biodiversity, e.g. moving from conventional to reduced tillage, banning burning of organic material and maintenance of grasslands. However, "discussions and data concerning soils and their sustainability 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). These narrow perspectives, often missing indicators and disconnected 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. The prevailing emphasis has also prevented soils from becoming a more mainstream "nature conservation priority" (Guerra et al., 2021). In 2018 no indicators on soil biodiversity could be provided to monitor the environmental performance of the post-2020 CAP, due to lack of data (Köninger et al., 2022). In forestry, which is differently regulated in the EU than agriculture with more legal incentives, there are science-based suggestions on how to manage production forests and conserve overall biodiversity (Tinya et al., 2023), though not many of these suggestions take soil biodiversity into account.

Protected species

Natural and anthropogenic processes influence the commonness and rarity of species in soil. In ecological terms, these are often caused by trade-offs in life history, but changing environmental conditions instigate extremes in these trade-offs (Jousset et al., 2017). For example, species with a highly specialised niche space may be highly abundant in a small number of locations, but rare overall and would be adversely affected by increasing homogeneity of soil habitats due to human activities.

Though protected species are rare among the soil organisms as the knowledge of their abundances and distributions is lacking (Phillips et al., 2017; Karam-Gemael et al., 2020). Lists of endangered soil organisms generally comprise of rare fungal species (Mueller et al., 2022) or earthworms (Stojanović et al., 2008), though the IUCN is beginning to establish a working group to guide identification of threatened soil species and here knowledge of taxa and their distributions and threats are crucial.

How soil biodiversity contributes to ecosystem functions and services

In the past decades, there has been a growing body of knowledge and awareness on the importance of soil biodiversity to ecosystem functioning and processes, though this is relatively small compared to what we do not yet understand. The research in the 1970 and -80, such as the *Man and the Biosphere* UNESCO programme, created knowledge on the significance of soil organisms in ecosystem functioning globally (Persson and Lohm, 1977). The scientific scope of ecosystems ecology today emphasizes functions and the role that soil organism biodiversity plays in understanding decomposition, energy fluxes or resilience aspects.

The ecosystem approach research has been developed over the years -through the concept of soil food webs and the direct and indirect interactions among soil organisms in order to 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) However, linking the diversity of soil organisms to the ecosystem functions at different spatial and temporal scales is a difficult process within the array of interacting soil organisms and evidence for direct diversity effects are rare and can also be explained by species identity (Mikola et al., 2002; Veen et al. 2019).

The importance of soil biodiversity to functions and ecosystem services has been thoroughly reviewed and with regards to phylogeny, biogeography, and diversity of important soil fauna groups (Wall et al., 2013). More recent research activities couple the diversity to both food webs and ecosystem services and show the importance of more diverse food webs to produce more ecosystem services and also that this is dependent on the diversity within the food webs (de Vries et al., 2013). The functions and services are also at risk at intensive management as the diversity decreases overall (Tsiafouli et al., 2015).

Main drivers of soil biodiversity change

To identify the main drivers of soil biodiversity change, an analysis by Work Package 3 (WP3) of the SOLO Project identified **D**riving forces, **P**ressures, **S**tate, **I**mpact, and **R**esponse measures (DPSIR) as fundamental components of soil health. These identified drivers will contribute to building the roadmap of this TT. Knowledge from previous research across the four land use types of agriculture, forest, urban and industrial areas, and natural areas also has contributed to a creation of an inventory of drivers of changes, with a focus on their potential to motivate the future change. This work is ongoing and will be integrated in fully in the SOLO project roadmap during 2024:

- Changes in use – drivers of anticipated changes in land-use
- Changes in management (i.e. land use intensity)– drivers of anticipated changes.
- Changes in land management quality – the use of future sustainable practices

Research on soil biodiversity conservation.

The importance of soil biodiversity to ecosystems and human well-being are often lacking in nature conservation literature and policy instruments. The conservation status of most soil organisms is almost completely unknown, but there is evidence that protected/conservation areas do not necessarily protect soil biodiversity (Guerra et al., 2021; Zeiss et al., 2022). While chemical and physical properties are relatively well known, we only recently have had access to the high-resolution and molecular tools needed to study biodiversity and function in soil (Guerra et al., 2021). As part of the 2018 LUCAS survey, 885 locations throughout the EU were sampled to study taxonomical and functional diversity in soil by metabarcoding. This will allow us to develop biodiversity indicators that may be considered for official inclusion in assessments and reviews of EU policies (Orgiazzi et al., 2022).

Köninger et al. (2022) analysed how EU legislation and directives address conservation of soil biodiversity. 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. The same goes for the 17 EU directives that Köninger et al. identified. All of them address issues, e.g. soil pollution, which could benefit soil biodiversity, but they do not explicitly address soil biodiversity per se. Soil biodiversity monitoring schemes in the EU member states often only focus on chemical and physical properties, but rarely on soil biology (Köninger et al., 2022), and out of the 196 parties of the CBD only a few had national targets (for 2011 – 2022) considering conservation of soil and soil biodiversity (Guerra et al., 2021).

Soil biodiversity conservation awareness and information sharing

To contribute to conservation and sustainable management of soil biodiversity, a few initiatives and research networks have been established over the years. Agreements 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 initiative is the Global Soil Biodiversity Initiative, a network of scientists, policy and public, that was established in 2011 that has given an international platform for assessing and synthesising knowledge in soil biodiversity.

The collection of data on soil biodiversity is a challenge that is brought to an only by the above-mentioned organisations but also by e.g. the GBIF (Global Biodiversity Information Facility), an international network and data infrastructure funded by the world's governments and aimed at providing open access to data about all types of life on Earth. In addition, the European Cost Action Edaphobase will create the structures, capacities and procedures necessary for expanding the existing data platform on soil fauna ("Edaphobase") into an open, publicly available data warehouse for Europe-wide soil biodiversity data as well as for developing tools that use and evaluate this data. Additionally, efforts such as the Soil Biodiversity Observation Network (SoilBON) https://www.globalsoilbiodiversity.org/soilbon are aimed toward systematically collecting observational data on soil biotic and abiotic factors worldwide to assess the condition of soil biodiversity and functions with a focus on the effects of protection/conserved status of the land area.

Future directions of soil biodiversity conservation

Tools available for research and innovation concerning conservation.

Currently, conservation practices and selection criteria for protecting landscapes do not benefit soil biodiversity and its associated functions. Tools available for conservation management of soil biodiversity specifically are few, but those that exist are underexploited as a source of information. There is large scope for integrating current databases and tools to be used as open access resources that would benefit research and monitoring efforts greatly. A development of AI techniques and synthesis of data to navigate and interact among databases could create timely innovation initiatives. There are currently global databases and resources that are used such as:

- Land Use and Cover Survey (LUCAS) datasets for all of Europe (JRC)
- Digital Observatory of Protected Areas (DOPA) (JRC) - https://dopa-explorer.jrc.ec.europa.eu/
- GBIF
- EUdaphobase
- IUCN Red Lists

For this reason, some critical activities of the SOLO project and Soil Mission is to engage with sectors that interface with and utilise soils in the course of their business. By raising awareness and educating stakeholders on the protection of and responsibility for the condition of soils, soil biodiversity, and soil health for the environment and its continued use as a resource, the Soil Mission partners with these interest groups to connect understanding and actions to beneficial outcomes for soil sustainability.

3 GAPs for all the Mission Objectives and Think Tanks.

3.1 Reduce Land Degradation

Despite the existence of various policies and strategies concerning Land Degradation, it is acknowledged that even if they are exploited to the maximum degree, it is hard to cover the whole aspect of land and its threats (European Commission 2022). Thus, land degradation continues.

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

By taking into account the above, it can be concluded that there are various knowledge gaps, and therefore, activities but also associated bottlenecks that should be considered regarding Land Degradation and the achievement of the aim of a LDN Europe in the upcoming years. Some of the major knowledge gaps, can be summarized below (European Commission 2019a, IPCC (Inter-Governmental Panel on Climate Change) 2001, Li et al. 2021, Romshoo et al. 2020, Li et al. 2021 Aouragh et al. 2023, Xu et al. 2023, Odebiri et al. 2023, Xie et al. 2020, European Environment Agency 2019, Reynolds et al. 2007, Hessel et al. 2014, European Commission 2015, Prăvălie et al. 2021, Guerra et al. 2016, Ravi et al. 2010, United Nations to Combat Desertification 2016, FAO 2015, Gisladottir and Stocking 2005, Intergovernmental Panel on Climate Change 2019, EU Soil Observatory 2019, European Commission 2020c, Daliakopoulos et al. 2016, The Economics of Land Degradation 2015, Economics of Land Degradation 2016, Saljnikov et al. 2022, Saljnikov et al. 2022, Lunik 2022, Reed and Stringer 2016):

Knowledge Gaps

- **Lack of comprehensive understanding of LD:** There is a lack of comprehensive and detailed understanding of the causes, processes, and impacts of LD across different regions and soil types. More research is needed to fill these knowledge gaps and develop a better understanding of the complexities involved and interlinkages between various drivers and processes concerning LD.

- **Current and future climate change interactions with LD in the EU:** LD and climate change are interconnected processes. However, there is still limited understanding of the exact interactions and feedback mechanisms between LD and climate change. An example can be found in the following questions: Which variables play a crucial role in monitoring the interactions and feedback loops between climate change and land degradation? What role do climatic factors play in either mitigating or accelerating land degradation, and how can emerging opportunities be harnessed to achieve Land Degradation Neutrality (LDN) within the framework of a changing climate? What is the impact of LD in Climate? As such, research is needed to assess the impacts of climate change on LD, as well as the potential of degraded land to contribute to climate change.

- **Current and future social-economical pathways interactions with LD in the EU:** The interactions between land degradation and socio-economic pathways represent a complex and multifaceted field of study. While there has been significant research in this area, several knowledge gaps still exist, such as understanding the long-term socio-economic consequences of land degradation, the factors that enable or hinder communities in coping with land recovering from land degradation, understanding the potential socio-economic benefits of suitable land management practices and integrating and validating indigenous and local knowledge. Addressing these knowledge gaps will contribute to a more comprehensive understanding of the intricate relationship between land degradation and socio-economic pathways, ultimately enabling more effective policies and interventions to mitigate and adapt to the impacts of land degradation.

- **Current and future biodiversity loss interactions with LD in the EU:** LD and biodiversity loss are interlinked processes. Despite this fact, there are several limitations in understanding the causal relationships and feedback loops between biodiversity loss and land degradation. More research is required to understand the impacts and synergies among land degradation and biodiversity loss.

- **Lack of LD-related data at different scales:** Without comprehensive LD data at different scales, our understanding of the causes and extent of land/soil degradation remains incomplete, making it difficult to develop targeted solutions and implement effective initiatives. Monitoring and assessing land and soil health, advocating for evidence-based policies, securing funding, and fostering collaboration all rely on the availability of accurate data. It is essential to prioritize data collection, digital transformation, and research efforts to support R&I initiatives aimed at addressing and mitigating LD.

- **Limited LD mitigations strategies:** There is a need for further research to optimize soil management practices, strategies and techniques that can help mitigate and prevent LD. More emphasis should be placed on developing innovative and sustainable soil management practices that are suitable for different regions, scales and cases.

- **Absence of well-established policies and legislations concerning LD and its components:** Lack of LD-related policies frameworks lead to unclear guidelines for soil management, resulting in a lack of standardization in R&I methodologies. While, this can be mainly seen as a bottleneck, it can also be characterized as lack of knowledge when interlinkages between drivers affects the process of establishing clear policies.

- **Knowledge gaps on the quantification of off-site LD effects and costs:** The contemporary understanding of land degradation (LD) is marked by a significant gap in knowledge, particularly concerning the quantification of off-site effects and costs associated with LD. This refers to the impacts that extend beyond the immediate area of degradation and affect surrounding regions or ecosystems. The existing knowledge deficit in this specific aspect underscores the need for up-to-date research efforts to address and quantify these off-site effects and costs comprehensively.

- **Insufficient knowledge for accessing funds related to LD and soil projects and initiatives:** Insufficient knowledge to navigate the administrative procedures for accessing funds related to LD and soils.

- **LD models' limitations, uncertainties and capabilities:** Despite the existence of several models and methodologies to assess the LD status or LD components, there is a limitation in understanding their capabilities and uncertainties due to the lack of validation data and long-term measurements.

- **Land/soil health and Ecosystem Services interactions:** The concepts of land/soil health and the ecosystem services provided by land/soil need to be supported by empirical evidence obtained through field and landscape indicators and measurements. It is worth mentioning that these measurements should be close to the reality of each region or case. Furthermore, ES include also cultural and aesthetic values, and thence it is important to investigate the connection between human well-being and all the variables that contribute to it. Moreover, collaborative methods are indispensable for resolving conflicts among stakeholders and gaining a comprehensive understanding of land and soil and its sustainable use over time. This necessitates the development of an advanced field diagnostic system that relies on dependable on-site measurement technology, complemented by expert-driven knowledge and assessment methodologies. Enhancing the field of soil science is crucial for making strides in the effort to mitigate and reverse land degradation. Additionally, the economic valorization of ES is a key point for their effective delivery.

- **Lack of sufficient understanding of urban soils in relation to LD:** As indicated in the Soil Mission Implementation Plan [10], the scope of land/soil degradation knowledge predominantly revolves around agricultural soils, with limited attention given to other land uses. It is necessary to bridge this gap and enhance our capabilities for supporting and rejuvenating land and soil health, both in urban and rural areas.

- **Difficulties in understanding the drivers of individual decisions associated with LD:** Understanding the drivers behind individual decisions is crucial for addressing land degradation effectively. Individual decisions made by land users, such as farmers or landowners, play a significant role in shaping land management practices. Despite advancements in research, there are still difficulties in understanding individuals' decisions as decision-making is dynamic (it evolves over time in response to changing conditions), is represented by an inherent diversity (decision-making heterogeneity) and there is lack of data to capture the behavioral factors.

- **Lack of understanding subsurface processes related to LD:** The insufficient comprehension of subsurface processes associated with land//soil degradation underscores a notable gap in current research and data acquisition efforts. In comparison to topsoil, subsurface processes have not received a proportionate level of scrutiny. This incompatibility is further exacerbated by the fact that a predominant portion of existing LD and soil datasets, as well as research projects and initiatives, predominantly concentrates on the topsoil layer.

Other prospectively identified Knowledge GAPs are listed below:

- Lack of understanding Nature Based Solutions: Not well studied yet.
- Is it possible to identify sets of adaptation options that complement each other, mitigating trade-offs and fostering mutually beneficial outcomes for both climate change and land degradation?
- At what spatial scale do LD vulnerability maps offer the most valuable insights to decision-makers while maintaining a rich level of information and detail?
- What resources are required for studying LD, and how do the monitoring (action) costs compare with the costs of not monitoring (inaction) across short, medium, and long-time frames?
- How do we pinpoint the thresholds, both in terms of time and space, at which LD adaptive practices and technologies may turn counterproductive, warranting discouragement of their widespread adoption?
- What is the optimal resolution and frequency of monitoring to provide decision-makers with crucial information on key variables associated with climate change and land degradation?
- How can we harmonize findings from monitoring both slow and fast LD-related variables?
- Is the concept of Land Degradation Neutrality (LDN) enough to ensure healthy land and soils in the future?
- How can we sufficiently control water resources to avoid provoking issues in soils? How the water directive could be adjusted?
- What is considered a ‘normal’ treatment for land and soil?
- What are the risks associated with LD and ice caps? What will happen and why?
- What are the proper LD definitions?

- What are the most efficient and cost-effective LD prevention and restoration measures, incorporating an assessment of trade-offs between different land uses and pedo-climatic zones?
- What are the most reliable thresholds, monitoring systems and indicators to estimate soil and land degradation in the EU?

Knowledge Implementation Gaps

- **Administering arable agriculture with a focus on organic carbon poses a challenge**, as the decline in organic carbon is linked to the difficulty of implementing existing knowledge into practice/practical policies.
- **There is insufficient awareness and recognition of the risk of arable land loss.** How can we effectively convey knowledge about this risk?
- **How do we educate and inform the population about the value of natural resources, including soil?**
- **How can we enhance regional planning in regard to LD?**
- **What are the green investments for LD?** Green investments for LD will facilitate EU actions concerning climate change and will result in much quicker reactions.
- **How can we overcome the challenges in land regulatory framework introduced by land ownerships?** As land is not a common good.
- **How do we support the farmers to make the turning point towards sustainable land and soil management practices?** Sometimes farmers might use management practices (e.g. ploughing) assuming that this will lead to an increase in their production. However, this is contradicting the reality as it actually decreases their production. While there is willingness to change as they can realize the current and plausible future production issues, there is a lack of knowledge on how to start changing and how to make the turning point.

Other prospectively identified Knowledge GAPs are listed below:

- How can farmers manage their animals more effectively in regard to LD?
- How can we alter the thinking-behavior of farmers and society towards LDN?
- What are the solutions, awarding-motivation schemes, and policies to revive farmers' hope?
- What are the means to further educate policy makers so they can support better practices towards sustainability and LDN?
- How do we shift from the current trend of increment of production- agricultural intensification to land conservation?

- How can we tackle the existing issues in policy implementation and how can we better align all the LD related policies with each other?
- How can we enhance knowledge transfer?
- How do we deal with the markets? There is a need to create a balance between LD and markets/ecological economics.

3.2 Conserve and increase soil organic carbon stocks.

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 gras and heath lands) and documentation on consequences of land use changes, impacts of urbanisation and new technologies on soil properties and soil organic carbon stores.

This “think tank” has specifically identified knowledge gaps connected to agriculture, forestry, biodiversity, soil health, climate change impacts, urbanisation, circular economy, education and awareness raising, as well on methods for carbon measuring, accounting and monitoring and very shortly on EU footprints of soil-C outside Europe.

The major knowledge gaps in how to conserve or increase soil organic carbon stocks are:

Forestry and practices

Research on forestry and practices require more long-term soil monitoring, experimental studies, and synthesis of existing data to provide evidence-based guidance for climate-smart forest management practices. Such as:

- What a different forest management practices affect soil carbon stocks and greenhouse gas emissions in different forest types, climates, and soil conditions.
- How forest management practices be integrated into existing modelling tools and accounting systems to better estimate the mitigation potential of forest soils
- How forest management practices balance the trade-offs and synergies between soil carbon sequestration, biomass production, ecosystem services, and socio-economic benefits.
- The carbon impacts of forest bioenergy are uncertain due to optimistic assumptions about forest management.
- It is also unclear how the potential effects of climate change and air pollution will affect forest productivity and carbon sequestration.
- Will the removal of forest residues for bioenergy have negative consequences on ecosystem services and long-term sustainability.
- Moreover, the effect of bioenergy demands on timber markets, carbon, and land use is complex and requires further studies.

Agronomic practices

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

- *Soil management*
  Many studies focus on varying one or two management practices (e.g., different tillage intensity, fertilization strategies or straw management), and how they influence soil carbon stocks. While the picture gets clearer for some aspects, others require more systematic long-term studies, e.g., fertilizer strategies for more novel organic fertilizers (biogas digestates, fish sludge etc.).

- *Soil tillage*
  The optimal combination of tillage and crop rotation for SOC sequestration depends on the specific context and objectives of each system. There is no one-size-fits-all solution, but rather a need for site-specific and adaptive management that considers the trade-offs and synergies between SOC, crop yield, and other ecosystem services.

- *Crop rotations and cover crops*
  How can we make use of cover crops to increase SOC in areas with climatic limitations to include cover crops in rotations?
  What is the potential of different plant species and mixtures to increase SOC in different climatic regions and farming systems?
  How do different plant species and mixtures affect greenhouse gas production?

- *System approach*
  There are few studies on a system level, e.g., comparing different types of regenerative systems in different climate zones and on different soil types with respect to processes affecting carbon stocks. Regenerative agriculture often includes periods of pasture or herbal leys within mainly arable cropping, so system level consideration including impacts of animals is required.

<u>Climate change and climate adaptation strategies</u>

The knowledge gaps on climate adaptation to sustain food and fibre production, while reducing or even increase the and soil organic stocks is a broad and interdisciplinary field of research, involving various disciplines, methods, and perspectives, such as.

- Climate change-related events such as droughts, forest fires, etc. are expected to occur more often in the next decades and will have an impact on soils. Modelling is needed to assess those effects on the soils and its capacity to sequester carbon.
- What is the effect of climate adaptation measures, e.g., breeding of more resilient varieties with larger root systems, longer-lasting plant covers.
- What significance do extreme weather events have on organic carbon stocks?
- How can forest management practices enhance the resilience and adaptation of forest soils to climate change, biodiversity loss, and other environmental changes.
- What incentives will be useful to make farmers and forest owners adapt different production strategies? It should be recognised that measures that are beneficial in these respects may not deliver benefit to farmers in the short – or medium term but may even represent a cost.

<u>Biodiversity</u>

There is a need for new knowledge on intensive use and land use change on soil functions and their impact on soil organic carbon stocks. Under which circumstances and why might plant biodiversity increase soil carbon (i.e., context dependency of where and why biodiversity is important)? Some of the unknowns are:

- Does the benefit of plant biodiversity on soil carbon storage depend on soil texture and parent material?
- Are monocultures of high-yielding plants superior to mixtures when the soil is heavily fertilized and irrigated?
- Are experimental results that manipulate the number of species or groups of species in natural systems applicable to agricultural systems that are often higher in soil fertility, fertilized and have improved cultivars of plants compared to native species?
- How does belowground biodiversity affect SOC stocks?
- Does a diversity of carbon inputs, from a mixture of plant species, promote greater stability of soil carbon than a monoculture of a high yielding species that has high inputs but all of the same litter quality?

Soil health – one health

There are still many knowledge gaps on how to measure, manage, and enhance soil health and soil organic stocks, especially in the context of organic and sustainable agriculture.

- Which carbon fractions are most relevant for stabilisation of carbon, which are the most relevant for soil health? As carbon stocks in soils change slowly, there is a need for developing and/or more extensive testing of more dynamic proxies for carbon sequestration.
- Can we both conserve soil carbon and benefit from its decay? How do we achieve increased decomposition of organic matter and increased stabilization of carbon at the same time? Should we seek to increase throughput of organic C in soils rather than concentrate solely on increasing stock as a better strategy?
- How do we determine the health of soils in terms of carbon content?
- Indicators based on measuring soil respiration are probably not the most appropriate. The wider issue is very important - perhaps we should seek to increase throughput of organic C in soils rather than concentrate solely on increasing stock.
- How can soil organic carbon stocks be assessed in an overall health concept that also includes healthy plants (food and feed), clean water, healthy animals, and people?

Circular economy

The soil plays a key role in a circular economy and sustainable society, but there is significant lack of knowledge concerning safe and energy-efficient recycling of waste materials in soil, and its impact on soil organic carbon stocks and soil health. We cannot make use of organic waste transferring contaminants, pathogenic organisms, and unwanted plant residues such as weed in healthy soils. Hence, we there are still knowledge gaps with regards to:

- How to deal with heterogeneity of organic waste samples and its following post treatment. This has implications for sorting and applicability.
- Many knowledge gaps still exist on how to treat issues like persistent organic pollutants (POPs) or contaminants of emerging concern (CEC).

- How the different sources and qualities of organic wates relates to soil carbon stocks and
- other soil health parameters
- There is a potential in recycling organic waste as valuable soil amendments and source for mineral nutrients. But the implications for GHG production is still uncertain.

Urbanisation

There is a need for more studies that assess the trade-offs and synergies between urban food production and SOC sequestration and explore the potential of sustainable urban food production practices. Several unsolved questions remain though:

- How can food production and other roles of soils and land use (such as flood control, nature conservation) figure more strongly in local and national planning?
- Preservation of high-quality soil should be an important principle. However, in some situations moving soil may be considered the last option when other measures to protect the productive land have failed. Hence:
    - How does moving of soil to an alternative location affect SOC stocks, both in the short and long-term?
    - What are the potential trade-offs' effects on SOC stock (e.g., change hydrology/drainage)?
- What consequences does decreasing agricultural production due to urban sprawl have on food systems elsewhere? E.g., any food not grown within Europe due to land loss is likely to be imported from elsewhere in the world often grown on land recently cleared of natural vegetation and thus emitting C.
- Is there a potential to increase SOC carbon stocks in urban soils?

Education and awareness raising:

There is a great need for education that increases awareness and knowledge of the soil and the conservation of soil organic carbon stocks in sustaining life and natural resources from the individual to the societal level. Soil is strongly under-communicated in society, including institutes of education at all levels, and there is an obvious link to the 8th mission objective on soil literacy in society, focusing on soil in general but also on its carbon stocks.

- The lack of awareness and appreciation of the multiple benefits and co-benefits of increasing and maintaining soil carbon stocks, not only for climate change mitigation, but also for soil health, food security, biodiversity, and ecosystem services.
- Many people are not aware of the importance and value of soil carbon for various soil functions and services, and how soil carbon can contribute to the achievement of multiple sustainable development goals.
- The trade-offs and synergies between soil carbon and other environmental and socio-economic objectives, and how to optimize and balance them in different contexts and scenario is generally poorly understood in the society.
- The spatial and temporal variability and uncertainty of soil carbon stocks and carbon-storage capacity are not well quantified and communicated, which hinders the assessment and monitoring of soil carbon changes and the evaluation of the potential and effectiveness of soil carbon sequestration practices.

- The lack of clear and consistent definitions and concepts of soil carbon storage and soil carbon sequestration, and how they differ from each other. Soil carbon storage refers to an increase of soil carbon stocks, while soil carbon sequestration implies a net removal of atmospheric CO2. However, these terms are often used interchangeably or ambiguously, which can cause confusion and misunderstanding among different stakeholders and audiences.
- The lack of effective and engaging communication and outreach strategies and tools to raise awareness and educate different target groups and sectors on soil carbon issues and solutions. Many existing communication and outreach activities on soil carbon are not tailored to the specific needs, interests, and preferences of different audiences, such as farmers, consumers, policymakers, educators, or media.

Soil carbon measuring, accounting, and monitoring

Several studies collectively point to the need for standardized, cost-efficient, and reliable methods that can be applied at various scales, and the potential of data-driven approaches and global frameworks to address these gaps (Acharya, Lal and Chandra, 2022; England and Rossel, 2018; Post et al., 2001; Smith et al., 2020).

- Need for standardized and cost-efficient methods, particularly in the context of financial incentives for landholders.
- There are challenges of detecting changes in soil carbon, calling for a range of approaches and tools.
- There are limitations of existing methods and proposes an integrated data-driven approach using machine learning and artificial intelligence.
- Credible and reliable measurement, reporting, and verification platforms, and suggests a global framework for monitoring soil organic carbon change.

EU footprints of soil carbon outside Europe

Current knowledge gaps to improve our understanding on soil organic carbon (SOC) stock outside Europe highlight the need for standardized estimation methods, comprehensive data sets, and accurate mapping techniques:

- The need for consistent estimation methods and data comparability.
- The need for baseline data for policy support and global change modelling.
- The importance of pedo-genetic SOC inventories for accurate estimation of land use changes.
- The impact of climate change on SOC stocks and the lack of regional data.
- The lack of a well-established relationship between SOC stock and ecosystem services.
- The potential for combining soil databases for topsoil organic carbon mapping.

3.3 No net soil sealing and increase the reuse of urban soil.

The H2020 project Soil Mission Support (SMS) completed in 2022 and the Soil Mission Implementation Plan had already identified some knowledge needs associated with specific objective 3 of the Soil Mission. Those initial lists were integrated through a fast screening of relevant literature and then complemented by the outcomes of the discussions within the Think Tank.

Knowledge gaps to achieve no net soil sealing.

1. Link between soil sealing and land take:
    - What is the degree of soil sealing associated with different land take processes? How does it vary in different contexts (e.g., for the same land use class across different countries)?
    - To which extent do the “no net soil sealing” and “no net land take” targets overlap?

2. Methods, data, and indicators to monitor soil sealing:
    - What approaches are more suitable to monitor soil sealing and land take processes at different scales? [8]
    - What methods and data are suitable to capture small sealing interventions at the local scale?
    - What indicators should be adopted to assess the impacts of soil sealing and land take? [7]

3. Scientific basis and applicability of non-binary classifications of soil sealing:
    - Would it be possible and desirable to move away from binary classifications of sealed vs. unsealed soils towards a more shaded picture based on soil properties and the impacts of sealing activities on soil health and functions?
    - To which extent could a non-binary assessment of soil sealing be included or support the development of innovative policies to achieve “no net soil sealing”?

4. Differences across Member States:
    - How are land take and soil sealing currently assessed in different countries (data sources, methods, indicators and reporting units, evaluation frequency)?
    - Are there indicators related to soil sealing and land take currently monitored and reported on across other EU level initiatives?
    - What common procedures can be established to monitor soil sealing and land take in EU Member States? [7]
    - What would be the reporting mechanisms of these indicators? And how will the monitored data be analysed and compiled to assess soil sealing and land take at EU level?

5. Effectiveness of actions to counteract soil sealing:
    - How effective are de-sealing/unsealing actions in restoring lost soils functions?
    - What is the potential of de-sealing interventions and how does it vary across different contexts (urban vs. non-urban areas, different types of settlements)?
    - How to identify suitable areas for de-sealing interventions and to prioritise them? [7]

6. Legal dimension of soil sealing:
    - How does the legal dimension of soil sealing, and land take vary across Member States and what are the opportunities to integrate the “no net soil sealing” objective? [8]
    - How do property rights and property regimes affect soil sealing in urban areas?

7. Societal dimension of soil sealing:
    - How does society perceive the relevance and need for the “no net soil sealing” and “no net land take” targets?

[8] Identified as one of the most important R&I knowledge gaps by the H2020 project Soil Mission Support (SMS)

- What is the level of awareness of the functions of soils across different categories of actors?
- What social, economic, and cultural factors drive the decisions of landowners and land managers about soil sealing? [9]

8 Fairness and legitimacy of "no net soil sealing" policies:
- How to minimise the negative impacts of "no net soil sealing" and "no net land take" policies on housing affordability and other material benefits?
- How to ensure that policies aimed at halting land take and soil sealing have fair impacts and do not exacerbate inequalities?
- What actions can be taken to enhance the legitimacy of reducing new land take and soil sealing against the demand of people?
- What tangible benefits of soil sealing reduction strategies can be stressed to enhance their legitimacy in the eyes of the urban and non-urban population?

9 Consideration of soil sealing in existing policies:
- To what extent are the concept of "healthy soils" and the importance and diversity of soil functions included in spatial planning? [7]
- To what extent have different policy instruments proven to be effective in supporting the "no net soil sealing" target?
- What policies have an indirect impact on soil sealing and land take? How to ensure that this impact is considered in their evaluation?

10 New approaches and instruments to reduce soil sealing:
- What is the potential impact of different strategies for sustainable urban development (e.g., densification, regeneration, greening through nature-based solutions, integrated water management) on soil sealing and land take?
- How to design effective policies making use of innovative tools such as compensation mechanisms and incentive mechanisms that integrate both push (costs of inaction) and pull factors (benefits from sustainable soil use)?

Knowledge gaps to increase the reuse of urban soils.

1 Quality of (urban) soils:
- 1.1 What is the quality of urban soils in Europe?
- 1.2 What indicators and protocols can be used to assess the quality of urban soil for their reuse?
- 1.3 What (cost-)effective methods and tools exist for the analysis?

2 Regulations on Maximum Limit Values:
- 2.1 What are existing regulations on threshold values for different reuse purposes (road and transportation projects, agriculture, urban development)?
- 2.2 How to implement Maximum Limit Values at EU-level for the assessment of urban soil quality for different reuse purposes, considering the differences in terms of quality of local soils and existing legislation?

3 Remediation and improvement techniques:

[9] Identified as one of the most important R&I knowledge gaps by the H2020 project Soil Mission Support (SMS)

3.1 What are the most cost-effective remediation techniques for urban soils that do not meet reuse standards?
3.2 How to select the most suitable remediation technique depending on the purpose of the reuse?
3.3 How to prove the quality of improved soil with an acceptable level of certainty?

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

5 Social acceptance of soil reuse:
5.1 What is the level of social acceptance of soil reuse? How can it be improved?

6 Barriers to soil reuse:
6.1 What are the most important barriers that currently limit the reuse of urban soils?
6.2 How do barriers to soil reuse vary across different EU contexts?

3.4 Soil Pollution and Restoration

The Soil Pollution and Restoration TT (PRTT) defines a schematic overview of 4 thematic categories, identifying the knowledge GAPs under this umbrella (see Figure 4). Therefore, this part first included the schematic approach developed and includes different types of knowledge gaps following these thematic categories. Additionally, some examples are provided.

3.4.1 Schematic appraisal of important identified research gaps

The PRTT carried out an appraisal of knowledge gaps regarding soil pollution and restoration, which will be continued during further steps. This activity entails an assessment of available knowledge gaps reviews, as well as additional already identified gaps and needs by the PRTT and stakeholders involved. Figure 4 provides a selection of key identified knowledge gaps, divided in four groups: “sources and loads of soil pollution”, “Affected soil properties, ecosystem services and impacts on livelihoods”, “Affected/Involved stakeholders and their role”.

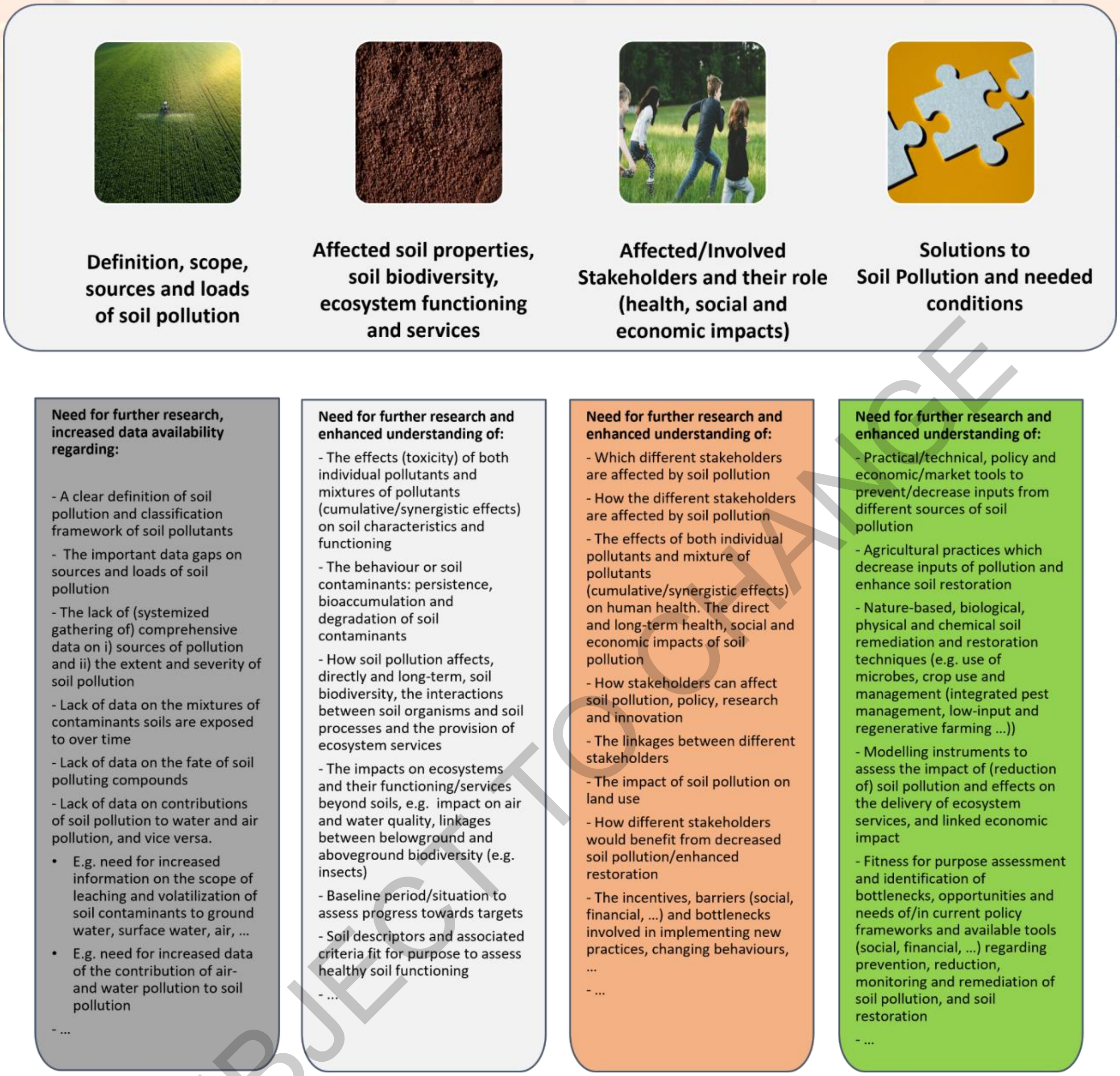

Figure 4: Overview of preliminary identified knowledge gaps regarding soil pollution and restoration.

3.4.2 Description of identified Knowledge Gaps

Knowledge gaps on the definition, scope, sources and loads of soil pollution.

1. Need for clear definitions regarding soil pollution.

In general, across different studies, projects and policy frameworks, different definitions and understandings on ‘soil pollution’. In view of policy frameworks, setting targets and progressing towards targets, there is a need for clear (agreements on) definitions. For example, the term ‘pollutant’ should be clearly defined, as there is a need to differentiate substances which are causing harm/negative impacts, or which are present without causing harm. E.g. substances added to the soil which are causing no harm could be considered contaminants. Substances that are causing negative impacts could be described as pollutants. There should also be made a distinction between naturally present, and human introduced pollutants. Moreover, a clear definition on a ‘clean soil’ is lacking. There is no clear understanding on what is considered a clean soil and a polluted soil. For example, should the definition of a clean or healthy soil entail the absence of pollutants/the lack of exceedance of defined concentration thresholds, or the absence of negative impacts on certain soil health descriptors and ecosystem functioning? The thresholds from which certain pollutants are considered harmful depend on the soil characteristics and are hence often country/region specific.

In view of policy frameworks and projects, there also is a need to define which soil pollutants are considered (e.g. pesticides, potassium, nitrate, mineral oil hydrocarbons, pharmaceuticals, microplastics, PFAS, newly emerging contaminants, …) and prioritised. A clear classification and prioritization approach is needed, in view of monitoring, setting targets and implementing management practices. In this regard, we also refer to the knowledge gaps on data, monitoring, indicators and thresholds/criteria.

2 Data gaps on soil pollution in soils and lack of systemized monitoring

A clear lack of data on soil pollution exists, linked to a lack of systemized monitoring frameworks. To fully assess the scope and possible impacts of soil pollution, needed management requirements and policy initiatives, increased data availability and monitoring are key.

In this regard, it is also needed to (further) develop classification frameworks for contaminants in combination with prioritization methodologies. A classification framework (e.g. decision tree) should take into account among more:

- The (eco)toxicity of contaminants and impact on soil health, ecosystem functioning and human health, determined by risk assessments. The interaction of the contaminant with other soil substances (e.g. other contaminants, organic matter, clay content, …) and living organisms. Mixture, synergistic and cumulative effects should be considered
- The prevalence of the contaminants
- Origin of contaminants
- Their persistence (short/medium/long term) and bioaccumulation
- Prevention and Bioremediation solutions
- Possible migration, evaporation and chemical phase change of contaminants of pollutants

The above criteria should also be considered to develop a set of soil pollution indicators, which are to be differentiated from soil health indicators. A contamination framework is essential for improved monitoring and remediation of soil contaminants and should be taken into account when designing monitoring frameworks, performing risk assessments, and setting policy and management priorities.

Also, the difficulty of monitoring substances should be taken into account. There is high diversity in the complexity of monitoring of different pollutants. For example, microplastics are very challenging to monitor. Also, newly emerging pollutants present an important challenge, and are key to include in monitoring frameworks, for example through generic chemical screening methodologies. Although prioritization approaches and practical feasibility are a prerequisite for effective gathering of data and monitoring, it is overall essential to monitor as many soil components/contaminants as possible. Materials which are currently not considered pollutants, could pose extensive problems in the future. Past experience has shown a large delay between substances ending up in soils, and the realisation of their negative impacts, resulting in far-reaching, long-term challenges for ecosystems, their services and human health. Currently there is a lack of understanding of the scope of contaminants/pollutants, including newly emerging contaminants, and their possible (future) impact on soil functioning. Enhancing and implementing methodologies to measure and predict the presence and impact of newly emerging contaminants are needed.

3 Behaviour/transportation and fate of soil pollutants and link of soil pollution with water and air

Extensive knowledge gaps exist on the behaviour, transportation and fate of many soil pollutants, as well as their interactions with water and air. For example, transport of pollutants via air, water and soils is a major factor in (diffuse) soil pollution. These three compartments hence need to be adequately assessed to evaluate (the impact of) diffuse soil pollution, demanding complex analyses (Geissen et al. 2015). Soil pollution is a major cause of groundwater and surface water contamination, and NOx soil emissions can have important impacts on air quality. Local pollution (e.g. contaminated sites) is via transportation processes also often linked to diffuse pollution. The interlinkages of the different matrices also entail important consequences for management of pollution. For example, when groundwater is contaminated, the costs and complexity of bioremediation of soils are greatly increased.

Processes of transportation (e.g. wind erosion) and air-water-soil interactions are highly dependent on soil characteristics and climatic conditions. Hence, a global approach is challenging, and site-specific evaluations are needed.

Knowledge gaps on affected soil properties, biodiversity, ecosystem functioning and services.

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

Significant knowledge gaps exist on the impact of soil pollutants on soil characteristics, including soil biodiversity, soil functioning and hence the delivery of soil ecosystem services.

For the majority of pollutants, there are no comprehensive (eco)toxicity data, and hence risk assessments, available (e.g. microplastics). When data on toxicity and risk are available, they are often limited to the impact of a single pollutant on a small set of organisms during a short time frame, often in controlled (laboratory) conditions. However, it is essential that cumulative and synergistic effects and long-term effects of pollutants in field conditions are taken into account, to assess the realistic impacts of soil pollution on long term soil health and ecosystem functioning. Although available research clearly shows the extensive impacts and possible impacts of soil pollution on soil characteristics, biodiversity and the delivery of ecosystem services, large data gaps remain. The high complexity of soil and interactions of soil compounds, organisms and contaminants provides a large challenge in assessing the full impact of soil pollution on the delivery of ecosystem services.

Again, it is important to note that the impacts of soil pollutants are site specific, as they depend on soil characteristics and environmental conditions.

5 Overall impact of soil pollution on wider ecosystem functioning (beyond soils)

On the one hand, soil pollution impacts the ecosystem services directly linked to soils, such as soil biodiversity, structure, aeration, control of erosion, nutrient cycling, water retention and buffering, crop health and growth, … On the other hand, soil pollution and transportation of soil pollutants also impact ecosystems far beyond soils, e.g. aquatic systems, vegetation, insects (links between belowground and aboveground biodiversity: many insects have a life phase below- and aboveground), mammals and other fauna dependent on soil health and biodiversity, pollination, …The full scope of these impacts is estimated to be extensive, but not comprehensively understood or assessed.

6 Baseline, Indicators/descriptors and quality thresholds/criteria

Connected to the knowledge gaps related to the need for clear definitions, there is a need to set a clear baseline for the assessment of progress towards targets. Currently knowledge gaps remain on how the baseline to set among more policy targets should be defined. For example, the baseline could be based on a set of soil descriptors and accompanying criteria.

Different indicators/descriptors and accompanying quality thresholds/criteria for assessing soil health have been described in scientific literature and applied by policy frameworks. However, a lack of understanding and agreement remains on which indicators and criteria to apply to define healthy soils and identify soils which need restoration. In order to efficiently set targets, and make progress towards targets, a clear understanding of both baselines, indicators and quality thresholds are key.

Knowledge gaps related to affected/involved stakeholders and their roles.

7 Impact of soil pollutants (individual and mixtures, short-term and long-term) on human health

Available research clearly shows soil pollution poses severe risks to human health, through different exposure routes (ingestion, inhalation, skin exposure). Drinkwater contamination, food contamination, transport of pollutants via dust to places frequented by people (paths, playgrounds, houses, gardens, …), ingestion of soil particles, … are a few important ways soil pollution can impact human health. In accordance with the knowledge gaps regarding the full impact of soil pollution on soil characteristics, biodiversity and ecosystem functioning, extensive knowledge gaps remain on the impacts of soil pollution on human health. For example, many uncertainties remain on the full impact of diffuse pollutants on human health.

8 Effects (social, economic, cultural) of and on different stakeholders

A variety of different stakeholders are involved in and/or impacted by soil pollution and restoration: citizens, scientists, farmers, industries (e.g. pesticide producers), water companies, policy bodies, …). For example, soil pollution has a wide impact or possible impact on stakeholders which directly or indirectly depend on ecosystem services delivered by or dependent on healthy soils, such as all citizens, farmers, drinking water producers, … A concrete example are farmers who engage in low input/nature inclusive/restorative practices, and are confronted with residues from previous practices or transported residues from other fields. Although available information shows clear and extensive impacts of soil pollution on these different stakeholders, the full scope of economic, social and cultural impacts is not fully understood. Correspondingly, also the potential benefits of soil restoration across different regions have not been fully assessed (e.g. quantification of ecosystem services).

9 Urban Soil Pollution

Urban soil pollution has been documented through several cases but has been overall poorly studied. Urban soil pollution is associated with specific challenges related to among more health, water quality (e.g. groundwater pollution) and risks for pollution of surrounding regions. Groundwater contamination, as well as transport of pollutants towards. Insights in the full impact of urban soil pollution, and clear frameworks and initiatives to tackle urban soil pollution, have been lacking.

Knowledge gaps related to solutions and needed conditions (supporting frameworks)

10 Technical/practical tools to prevent agricultural and non-agricultural soil pollution.

Although many management practices and technologies, including Integrated Pest Management strategies, agro-ecological and regenerative practices, monitoring systems and precision farming and biocontrol, are available to reduce agricultural soil pollution, it is apparent that significant challenges remain in their uptake. Moreover, further research is still needed to develop and/or optimize these practices for more cropping systems in different climatic and environmental conditions. For example, the use of functional biodiversity in increasing natural pest control and decreasing dependence on pesticides is a highly complex field, which needs specialised adaptation to specific cropping systems and environments.

11 Technical/practical tools to remediate soil pollution and restore soils.

Current available techniques to remediate soil pollution, such as management practices, crop use, the use of microbial technologies, are in need of further research and development to improve remediation effectiveness. Microbial technologies carry great potential, however, still need further development regarding increasing efficiency. The process is highly time consuming, which is considered a significant bottleneck in the field of bioremediation.

12 Which policy tools are available to prevent soil pollution, and are they fit-for-purpose?

Different legislations related to soils are implemented at national level. However, there is a strong need to harmonize different legislations which relate to soils. Sometimes different legislations contradict (e.g. law on soil protection and law on fertilization in the Netherlands). At the same time, important gaps in legislation exist regarding large-scale monitoring and managing of soil pollution. The EU proposal for a Soil Monitoring Law aims at addressing part of these challenges but is characterized by important gaps regarding e.g. soil biodiversity and soil pollution, namely diffuse pollution. Also, clear binding and time bound targets remain absent in the proposal, as well as a clear link with groundwater and surface water pollution and legislation. Hence, important knowledge gaps exist regarding if current legislation and legislation under development will comprehensively address policy needs regarding soil pollution.

13 Socio-economic and market tools to prevent soil pollution/fitness-for-purpose.

There is a need for further assessment of available and needed socio-economic and market tools to prevent soil pollution and restore soils. These include incentives and financial support (public and private support), and business models based on soil health, decreasing the soil footprint, remuneration of ecosystem services and stimulating innovation. Public funds need to be directly linked to soil restoration, and not support activities polluting soils. Different market failures contribute to the problem of soil pollution, for example insufficient/heterogeneous internalisation of environmental costs in the EU and beyond, lack of soil data, and a lack of implementation of the polluter pays principle.

14 Which initiatives exist and are needed to involve farmers in soil restoration and prevention of soil pollution?

Different initiatives involving the reduction of soil pollution and enhancement of soil restoration by farmers have been developed. However, a comprehensive overview of all relevant initiatives is needed, as well as, if relevant, information on reasons for discontinuation. This information should contribute to an analysis on which initiatives and supporting conditions would be still needed to increase uptake of good practices throughout Europe.

15 Bottlenecks regarding the implementation and upscaling

Further insight is needed in the bottlenecks and enhancing conditions regarding the implementation and upscaling of relevant and valuable techniques to prevent soil pollution and enhance restoration. While many effective techniques to prevent and remediate soil pollution exist, a comprehensive, clear overview on what is preventing their uptake is needed.

16 Modelling

There is a need for further development of modelling tools to assess in an integrative way the impact of soil pollution and the impact of reducing soil pollution and restoring soils on ecosystems and ecosystems services and associated economic impact.

3.4.3 Examples of identified research gaps regarding pesticide pollution.

Below, examples are given of knowledge gaps already identified during our literature review related to pesticide pollution. Many of these knowledge gaps are also applicable to other sources and types of soil pollution. The below overview will be further developed by the PRTT during the project, to result in a comprehensive overview of the main research gaps across all domains and subdomains of Figure 1. This list is hence not final and consists of a selection of important examples.

Scope of pesticide pollution

While the minimum number of soil sample points in the EU needed to provide a statistically reliable measurement of soil health on a regional scale has been estimated at 210 000 points, there are currently 34 000 points at Member state level, 41 000 from the LUCAS Soil campaign of 2022 of which 20 000 is a repetition of previous LUCAS Soil campaigns. A large data gap exists on pollution loads and their fate in the environment. Data from member state level are mostly also not available at EU level. Monitoring schemes are often fragmented, existing of different sampling methods, frequencies and densities, resulting in a lack of comparability. Also, the consistent storing of soil data in an accessible database is lacking. While the LUCAS soil survey provides an overarching monitoring framework, it currently lacks clear legal mandate, and guaranteed continuity (EC Working Document - Impact assessment report, 2023).

Pesticides have not been systematically monitored in the EU. Available data originate from the LUCAS Soil survey and from several monitoring and research projects carried out throughout Europe (Silva et al., 2019). Available data show that pesticide mixtures in agricultural soils are the rule rather than the exception. For example, a large monitoring study analysing 317 soil samples, found that 83% of soils contained 1 or more residues, with 58% containing mixtures of pesticide residues, existing of 166 different mixtures (Silva et al., 2019).

Monitoring of pesticide residues in soil has not been mandatory in the EU, and large-scale studies on soil pollution by pesticide residues are very limited. Often, they also focus on one pesticide, or a smaller group of compounds (Covaci et al., 2002; Ružicková et al., 2008; Silva et al., 2018). Sampling that has been carried out often used different sampling strategies and analytics. Hence, an overview of the distribution of pesticides residues across the EU has been missing.

Also, data on pesticide use are not currently available at EU level but become mandatory from 2028 through the Regulation on statistics on agricultural inputs and outputs.

Effects on Biodiversity, Soil Functions and Ecosystem services

In general, current risk assessment doesn't capture cumulative and combined exposure to pesticides, and resulting impacts on soil biodiversity, overall biodiversity and ecosystem functioning (Bopp et al., 2019; Devos et al., 2022; Sousa et al., 2022). Risk assessment also focuses on the active substances of pesticides and doesn't take into account the full impact of the product (active substance, co-formulants and adjuvants) (Mesnage and Antoniou, 2018; SAPEA, 2018).

Thresholds for a few pesticide residues have been part of the legislation of a few European countries (Carlon, 2007), but mostly for currently banned and highly persistent pesticides (e.g.) DDTs, HCHs, Atrazine, …). Furthermore, the lack of data on pesticide mixtures in soils, as well as data on the total load of diffuse contamination in soils, have prevented validation and improvement of current risk EU assessment of active substances and pesticides. The latter is currently based on prediction of environmental concentrations, based on recommended application rates. The in-soil indicator organisms used in EU risk assessment only exist of a limited set. Research has pointed at the lack of field data and lack of information on mixture and cumulative effects on soil organisms, including non-standard and native species and communities, soil functioning and ecosystem services (Geissen et al., 2021).

Although some studies have carried out economical assessments of the impact of agriculture on the environment, the environmental externalities of pesticide pollution haven't been fully assessed across Europe. Likewise, benefits of decreasing soil pollution and positive impacts of restoring soil health on biodiversity and ecosystem services, including long-term, sustainable production of food, haven't been comprehensively included in current evaluation assessments, including in existing models. For example, models assessing the impact of reducing pesticides often don't consider the medium- and long-term positive impacts regarding crop production which could result from soil restoration and enhancement of ecosystem services, such as increased pollination, natural pest control and protection against erosion.

Effects on human livelihood

Analogous to the research gaps regarding the assessment of the full impact of pesticides on the environment, the complete impact of total pesticide exposure through all exposure routes, taking into account complete products, mixture and cumulative effects, for human health remains currently unclear. For example, current risk assessment focuses on pesticide exposure through food ingestion, while research shows exposure via air and skin are main routes of exposure. Carried out research projects show widespread pesticide contamination in soils, air, waterways, indoor dust, animals and humans. However, systematic monitoring data of pesticide residues in humans and indoor dust are not available. A large body of research shows the links between pesticide exposure and a variety of health impacts. Certain illnesses, such as Parkinson's disease, have been listed as occupational disease in France, due to their high prevalence among farmers and farmworkers. A comprehensive assessment of toxicity effects of pesticide mixtures and cumulative effects, spatial analysis of pesticide exposure and prevalence of specific health impacts in Europe is needed to assess these impacts further.

Impact on and of stakeholders

⟶ Policy makers

Currently, different relevant legislative processes are ongoing, with the aim of contributing to a comprehensive protection of the environment, including soil health. Many uncertainties remain on how and if policies underway will be fit for purpose to reach goals set by the Green Deal and the Soil Mission, and how they will be interlinked. For example, linkages between policies under development and current legislation, such as the Common Agricultural Policy, are uncertain. These linkages, as well as effective result-based implementation of legislation, are deemed essential to reach soil related goals. Current and past legislation have been frequently not adequately implemented. An important research question is hence how to ensure consistency and needed linkages between different policies, and how to ensure effective, result-based implementation of legislation, as well as monitoring of the results of policy measurements and application of feedback mechanisms.

→ Farmers

Many projects and initiatives throughout Europe have focused on gathering and exchanging insights and knowledge regarding from and between farmers, between farmers, research and policy. Projects focusing on lighthouse farms, practical demonstrations and cooperation and knowledge exchange across groups of farms have been identified as valuable and effective. However, a recurring bottleneck is the lack of continuity of projects, and the lack of further, large-scale implementation of management techniques which have been found successful. An important identified research question is hence how to create optimal overarching frameworks to successfully implement successful agricultural management practices based on prevention and enhancement of ecosystem services, including healthy soil functioning, at a large scale.

Solutions to soil pollution

Preventative measures

In general, pesticide use is heavily subjected to 'locked-in' mechanisms regarding agronomy and research, economics, knowledge and policy, which have prevented reducing pesticides. These locked-in mechanisms, and barriers to overcome them, have been identified by the ongoing Sprint project.

Successful examples of preventative, low-input and nature-inclusive agricultural practices have been applied throughout Europe. Integrated Pest Management (IPM), which is based on preventative measures, increasing natural pest control (beneficial organisms) and the resilience of cropping systems against pests, while only using chemical pesticides when all other methods have been exhausted and failed, is mandatory in the EU since 2014, through the sustainable use of pesticides directive (dir. (EC) 128/2009, SUD). Multiple analyses of EU bodies2 have pointed at the lack of implementation of IPM since then. The proposal for a Sustainable Use of Pesticides Directive (EC 2022), which will replace the current directive, was published by the European

Commission as an answer to the lack of pesticide reductions and implementation of IPM since 2009.

A wide variety of examples of IPM practices is available for diverse cropping systems throughout Europe. The European Commission recently published a database of 1300 examples of practices, techniques and technologies for IPM, including 273 crop-specific guidelines, accompanied by a study assessing their effectiveness3. However, the supporting framework to implement practices, such as independent advisory systems, and hence access of farmers to alternative management techniques, has been lacking in most member states. On the other hand, more research is needed to further develop and optimize IPM practices for all cropping systems and environmental conditions.

An important lock-in mechanism consists of the fact that policy, funding and infrastructure mechanisms are focused on supporting a limited set of farming models and major crops. For example, current agricultural legislation and funding doesn't secure linkages between funding and protection of the environment and enhancement of ecosystem services (OECD, 2023).

Important examples of research topics to include in the roadmap are hence:

- How to overcome lack of implementation of current policies and increase accessibility and wide-scale implementation of existing alternatives

- How to secure linkage and coherence between policies, advisory systems, funding/tax mechanisms, value chains and ecosystem services.

- How to further optimize agricultural management practices based on preventative measures, covering existing cropping systems and environmental conditions throughout Europe.

3.5 Soil Erosion

While our current knowledge base is robust, there is a crucial need for a deeper comprehension of both natural and anthropogenic soil erosion processes, especially focusing on their intricate interactions. Addressing this knowledge gap requires a concentrated effort on interactions operating across diverse spatial and temporal scales, with an emphasis on predicting rates and assessing both onsite and off-site impacts.

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

Furthermore, the evaluation of soil erosion rates should broaden its scope to encompass a spectrum of erosion processes at various scales – from local to global. These include splash, laminar, rill and gully erosion, subsurface erosion (such as piping and tunnelling) or riverbank erosion. Some human interventions are known to increase soil erosion, such as erosion induced by tillage, land levelling, soil quarrying, termite mound removal, explosion cratering, and trench digging. It is also needed to deepen and clarify the key factors that may trigger soil erosion in each scenario, such as the increase in exposed bare soil but also the increase in soil compaction or a combination of both (Prats et al., 2019).

While acknowledging soil erosion's relevance, we currently lack a comprehensive understanding of its role in other critical processes, such as carbon budgeting, transport and fate of contaminants, nutrient loss, climate change and biodiversity. It is imperative to quantitatively represent the losses of ecosystem services following soil erosion and concurrently occurring soil degradation processes.

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

The effects and trade-offs of land management practices, water management (including irrigation and drainage), and climate change (including greenhouse gas emissions) remain inadequately understood. Bridging this gap requires comprehensive monitoring data, which is currently the primary knowledge deficit in the soil erosion field. Establishing a Soil Erosion Monitoring Network at the EU level, incorporating local-scale monitoring systems (involving citizen science activities as well), is essential to address this gap (Prats et al., 2022). Integrating multiple scales is paramount for improving future soil erosion assessments.

The collected data could facilitate real-scale estimations of soil losses and their correlation with contextual information, such as management practices, crop types, and rainfall density. Aligning monitoring efforts with appropriate spatio-temporal scales is crucial for identifying specific erosion processes occurring at different scales. Exploring the potential of artificial intelligence and remote sensing is essential for gaining a more nuanced understanding of soil erosion processes, enhancing data collection systems, and improving modelling capabilities.

The initial phase of developing prediction models is crucial for decision-making involving effective monitoring (Parente et al., 2023). Calibration and validation of existing models need attention, emphasising the compilation and analysis of data at a meta level. Data mining on existing soil erosion and sediment yield data is necessary to enhance the accuracy of modelling tools. Although current modelling capacity allows consideration of the effects of management practices (such as gully and tillage) and geomorphic processes (such as land sliding and riverbank erosion), there is a lack of quantification of these effects. Models also need to be linked to the consequences of soil erosion, especially within the context of climate change (Borrelli et al., 2023).

Finally, recognizing the pivotal role of policy in local decision-making processes, it is imperative to identify trade-offs between policies and test strategies to mitigate them (Petratou et al., 2023). Currently, we have policies that indirectly induce soil erosion while achieving benefits in other dimensions; such trade-offs need to be systematised and alternative policy designs tested (Rodriguez Sousa et al., 2023).

Knowledge Transfer Gaps

While soil erosion control measures already exist, an effective strategy requires the systematic organisation of these measures tailored to the specific situations where soil erosion poses a problem. There is a pressing need to assess, improve, and develop both current and innovative soil erosion control techniques and field strategies to promote sustainable soil use. Prioritising the utilisation of nature-based solutions and targeting soil erosion hotspots and off-site effects should be a primary focus.

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

Urgent steps must be taken to increase awareness of soil erosion and the potential threats it poses. Society needs to be more cognizant of the current situation, facts, threats and the preventive measures required (Prats et al., 2022). Developing a comprehensive guide on the importance of soil, the risks associated with soil erosion and loss, impacts on life on Earth, ecosystem services, and food security is essential. This guide can serve as a valuable tool for raising awareness and educating individuals, starting from primary school. Concrete and enlightening examples should be used, in order to create a real impact on the target audience. Involving citizen science activities may help in the recognition of the real scale of the problem and in raising awareness in the wider society.

Soil erosion prediction scenarios should provide information on the magnitude of consequences, including off-site effects and subsequent risk assessment (Parente et al., 2023). Developing "severity maps" as policy tools to indicate hotspots requiring immediate action is crucial and should be prioritised for swift development. Their development must be accompanied by a sound delimitation methodology, as well as by effective norms regarding authorised land use and its monitoring.

Box 3. Example I

In Portugal, the creation of the National Ecological Reserve has, in an innovative approach, contemplated “areas at high risk of hydric soil erosion”. However, the methodology to define their boundaries is inadequate and non-consensual, and, furthermore, there’s a need for effective regulatory guidelines that tackle not only the authorised land use types in these areas, but also their control.

Knowledge Implementation Gaps

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

While monitoring systems and modelling tools play a pivotal role in supporting and enhancing decision-making processes, it is equally essential to engage with managers and landowners. Understanding their motivations during land management is critical, and collaborative approaches need to be developed jointly.

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

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

Box 4. Example II

To comply with the Common Agricultural Policy's objectives, the Portuguese government subsidizes shrub clearing, even when that type of vegetation is not only an integral part of the agroforestry systems, but also a fundamental element in controlling soil erosion in areas which are particularly vulnerable to desertification.

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

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

3.6 Soil Structure

But with soil being diverse, what is the best structure? Or should we define the structural quality of soils according to their resilience to climatic disturbances, such as varying weather conditions and/or management practices such as tillage, chemical inputs. Or due to the importance of water on soil functionality, should the optimal structure be connected to water retention capacity or to habitat provision for biodiversity and complexity of the habitat? And how we can take into account the relative importance of these different ecosystem services provided by soil structure in different pedoclimatic zones, soil types and land-use types.? And how this relates to the productivity of soil, productivity of what and in what conditions? Soils and their structure can change, how about thawing permafrost or restored soils such as peat? Last, how to get the info on best practises to the actors when they are so diverse group?

<u>How to measure soil structure</u>

Assessing the soil structure holds a great variety of analysis methods, each of them emphasizing different aspects of soil structure and possibly being suitable for only certain kind of soils. Methods may also be suitable only in the field, in monolites or only in the laboratory, or only for the intact or homogenized soils. Some methods are cheap and widely used, but less informative and difficult to be interpreted, while certain new methods are informative but expensive and need rare equipment. Potential methods include for example the following:

1. Water retention curve and pore-size distribution
2. Water infiltration
3. Hydraulic conductivity
4. Air permeability
5. Water holding capacity (WHC)
6. Field capacity
7. Aggregate size distribution and stability

8. Bulk density
9. Visual soil assessment
10. Aggregate formation
11. Penetrometer measurement
12. Rooting of seeds into soil core
13. IR and NIR spectra
14. X-ray tomography for morphology of the structural features (pore structure and connectivity)
15. Sentinel and other satellite 100m grid--> 25m now.

Land management.

Naturally forest fires and its recurrence modify soil properties, functions and soil resilience. **Soil compaction due to heavy machinery or erosion affects** soil physical properties (e.g. bulk density, water retention characteristics). This can lead to changes in leaching of nutrients and carbon. The emerging issue of microplastics in European soils is conceptually also a physical contaminant and affects soil bulk density. Changes in the soil nitrogen availability, C/N ration, pH as well as cation exchange capacity and base saturation are parameters that may reflect the ecosystem services provided by soil. Compaction may cause problems for soil organisms and their function. For example, their biological activity may decrease affecting the decomposition of soil organic matter, maintenance of soil structure (exopolysaccharides, glomalin, fungal hyphae). The improvement of soil structural quality can be assessed by physical-structural-hydrological parameters (agg. stability, MWD, pF-curves, bulk density) linked to soil microbiology (at least, Microbial carbon, Basal soil respiration, Enzyme activity). There is a gap that should be explored between soil physical-structural and biological builders of soil structure. A particular challenge is that in many cases soil in poor condition is not responsive to management practises as it should.

Soil operations affect soil structure, timing of the operation is important. However, we need more knowledge on adaptive timing. Also, 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.

We need information on soil specific management options in different climatic conditions and land-use systems to improve and functionality of soil structure.

Aggregate formation

The **cementing agents that link soil aggregates are well-known**. Large aggregates are in their majority earthworm casts. These earthworm casts are an untruthful aggregation compared with the good aggregation that is produced under the grass covers. Small and fine roots produce optimal conditions to form and to stabilize aggregates due to the polysaccharides produced by the microorganisms. Furthermore, the roots maintain the aggregates mechanically separated. 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.

An increase in **aggregate stability** provoked by an increase in organic matter seems to be effective only from a given threshold, established between a 5% or 6% of organic matter content. Soils with low SOM content, the aggregation is controlled by other cementing agents (iron oxides, aluminosilicates). But do we know the importance of the biodiversity, or turnover, of soil virus, bacteria, soil biota in the stabilization of the soil structure?

In addition to aggregates, it is also useful to consider the pore network and the pore network structure. From a biological perspective it is potentially much more pertinent as the pore network is the habitable space for microbial species. Ecosystem engineers such as earthworms also form biopores.

Weather events

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, for example for the lack of frost period due to milder winters, certain machinery cannot be used without causing dramatic effects to the soil structure. Thus, the proper winter in Northern Europe with frost period protects soils from damage and allows use of heavy machinery (in forests). In addition, frost and the freeze thaw cycles are known to improve structure in arable soils by maintaining a good distribution of aggregate size. Unfortunately, currently climate change appears as milder temperature and increased precipitation in winter period, leading to greater leaching of organic material from the soils. Increased occurrence of heavy rain is possible also in more Southers 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 alter soil stability. In addition, the possibility for increased leaching is not restricted only to organic matter but may concern also particulate material (suspended solids) as well as nutrients essential for e.g. forest ecosystems in the long run. (Machado et al., 2018b)

Biotic part of soils

On forest land there is a growing interest among landowners towards sc. continuous cover forestry, where one avoids clear-cuts and site preparations. If continuous cover forestry practices get more common and grow in area that results a significant change by reducing the need for soil preparation and for maintenance ditching 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 covers 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. One interesting approach has been mimicking natural plant succession. Plant breeding has changed root exudates, root microbes, soil chemistry via microbes, lack of AM, glomalins and other EPS.

We need information, not only on agricultural soils, on the physical-chemical processes, all the biological processes and interaction from larger plants and animals to fungal hyphae and tiny microbes. How soil organisms interact with each other, and the abiotic environments affects soil structure. Soil invertebrate effect has been neglected for crop production. The biotic part maintains the structure, how is it affected with climate change and changes in soil as a habitat? How do soil animals and microbes respond to the extreme events. In addition, the role of microbes in presence and absence of OM can differ and should be understood.

How does biodiversity change? And how does this affect the extracellular polymeric substances produced by microbes and affecting strongly soil structure? In forests, how does the forest stand age and management affect the resilience of soil to draught and heat waves, and how the soil responds to the drought. Do different management practices bring along forest floor vegetation changes mediating the effects of drought on soil? Forest fires in Portugal is a major threat (500.000has burned only in October 2017) affecting soil structural, soil biota, soil physico-chemical with also off-site effects (flooding, ash deposition in damns, …,). Besides that, forest management practices affect soil structural properties (timber extraction, land preparation by terraces, and so on), forest fires themselves modify environment, being a major threat.

Last gap is linked to the recovery of soil which is tightly linked to soil structure. How long does it take to recover and how do we measure soil recovery?

3.7 Reduce the EU global footprint on Soils.

This section provides the knowledge Gaps that the EU global footprint on Soils developed. The nature of the TT has an important international component that differs with the rest, and therefore its insights. Here the list of the Knowledge Gaps and their description are presented.

Narrow focus on biomass

Some background: This first knowledge gap stems from the narrow focus for the EU global footprint on biomass, food and timber in the current Soil Mission Implementation Plan. Semantically, it might thus not be considered a knowledge gap, but by ignoring it, a strong knowledge gap could persist in the future, because a major part of the potential footprint of EU actions on soils worldwide is ignored.

Multiple stakeholders placed a strong remark regarding the clarity of the actual goal of this mission objective. It is not clear why this is limited to biomass. If one would take this definition strictly, land degradation from industrial soil contamination (importing other products) and from open mining importing mineral resources will not be taken into account. Still, these can have a profound impact on global soils. 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 to make a baseline for global footprint on soils of EU actions. If this is the goal, the objective should be renamed as 'reduce the impact of EU food, feed and fibre imports on Global Soils'.
Potential path forward: it was suggested to focus on a broader definition in the mission objective, so that full impact can be assessed, and future suggested policy actions should include non-biomass and non-food related soil footprint.

There is no standard soil foot printing methodology.

As already emphasized in the state-of-the-art and background, the Soil deal for Europe mission acknowledges that even in EU soils, it is difficult to assess an overall status of soil health. A key obstacle to EU-wide quantification of soil health is the lack of systematic and harmonized soil monitoring across member states. Unlike other resources such as water, there is no legal requirement for EU member states to report on soils. This results in varying levels of soil monitoring and hinders the ability to effectively monitor and report on the health of European soils.

This is testimony to the formidable task that is ahead for achieving soil mission objective 7, which brings together all EU-based mission objectives, with all related harmonization and integration issues, into one worldwide perspective.

During the Barcelona SOLO meeting, a LULUCF based CO2-emission tracking methodology was proposed. This would start from considering different categories of land use, e.g. forests, croplands, grasslands, wetlands, settlements, each with a different impact on soil health and soil functioning related variables, and each with a standard indicative value for a specific soil ecosystem service. The latter could be based on multiple tiers for detail, depending on availability of data for a certain region. Based on land use change tracking, changes in soil functioning can thus be assessed, and a footprint can be associated to it. A MRIO based analysis as described earlier in the SOTA, can be used for linking local land-use changes to global production and consumption patterns, and in particular for linking impact to EU action.

Trade-offs between soil impacts

As the outside EU foot printing mission sub-objective heaps together different soil impacts into one assessment, unlike the mission objectives oriented towards the EU-27 soils, a new challenge will arise, with trade-offs between regional impacts and between different key focal impact areas. Even if a clear baseline for some functions is established, there will always be trade-offs with other functions. 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.
In the SOLO meeting in Barcelona, multiple stakeholders discussed key soil functions to focus on, as efficient assessment will require focus. The suggested key focus impacts are: GHG-emissions and soil carbon sequestration, soil biodiversity, soil structure (linked to soil erosion), water system health and pollution and pesticides/herbicides impact, soil nutrient status.

Scale issues.

Data availability is mostly regional and not EU-specific. How to move from case studies to a baseline for global EU impact? How to link the changes in soil to EU policy and actions, and how to distinguish impact from other local and global impacts? Here is also a matter of scale: at which scale will it be possible to define the impact/EU action relation?
During the Barcelona SOLO meeting, an initial focus on key trade regions and key crops and agricultural products to better understand the potential solutions to these scale issues:
Key crops: timber, cocoa, soy, coffee, cattle, oil palm and rubber
Key regions: Brazil, African Union, Vietnam, New Zealand, Indonesia, Canada

Impact of local and broader outside EU policy and soil governance

The EU footprint, and any actions related to reducing it, will also be impacted and interacting with local policy actions. This might complicate both the definition of potential EU actions to be taken, and of footprint establishment. It will be key to carefully map and take into account local policy when defining EU actions.

Potential benefit of the use of new biotechnology and bio-synthetic technologies, as well as agro-ecological approaches

Multiple stakeholders mentioned that there is a key knowledge gap regarding the potential of new biotechnology and agro-ecological approaches to lower the footprint of EU food import. This should include changes that EU can implement within its own food system to reduce its dependence on outside EU food sources.

Link to other soil mission objectives.

Again, the last key knowledge gap is more of a potential future key knowledge gap than a current key knowledge gap. But should it not be taken into account, strong incompatibilities between this specific mission objectives, and mission objectives targeted to within EU action could arise. Other mission objectives focus on EU soils mostly, without having to consider global impacts. Risk of EU solutions with footprint abroad is strong. We need to include actions taken in other mission objectives in a footprint analysis. How to achieve this is currently unclear.

Table 2: Roadmap table

Narrow focus on biomass	Unclear why this objective is limited to biomass. Taking this definition so strictly, land degradation from industrial soil contamination (importing other products) and land take (e.g. from open mining importing mineral resources) will not be taken into account. Still, these can have a profound impact also on global soils. A too narrow focus on biomass flows hampers baseline establishment of full impact.
Lack of focus on actions that can be done without baseline	Other objectives could be defined: would reaching land degradation neutrality, in regions where imports are produced, be a potential alternate base target for the mission? Do we risk of ending up in a complicated task to establish the baseline, which hampers immediate focus on solutions, which can be suggested even without baseline establishment?
Trade-offs between soil impacts	Multiple soil impacts can be defined. Here a new challenge will arise, with trade-offs between regional impacts and between different key focal impact areas. Even if a clear baseline for some functions is established, there will always be trade-offs with other functions.
How to upscale case-studies	Data availability is mostly regional and not EU-specific. How to move from case studies to a baseline for global EU impact?

Impact of local and broader outside EU policy and soil governance	The EU footprint, and any actions related to reducing it, will also be impacted and interacting with local policy actions. This might complicate both the definition of potential EU actions to be taken, and of footprint establishment
Lack of data on larger scales	How to link the changes in soil to EU policy and actions, and how to distinguish impact from other local and global impacts? Here is also a matter of scale: at which scale will it be possible to define the impact/EU action relation?
Trade-off between EU based soil actions and export of pressure to global South	Other mission objectives focus on EU soils mostly, without having to consider global impacts. Risk of EU solutions with footprint abroad is strong. We need to include actions taken in other mission objectives in a footprint analysis. How to achieve this is currently unclear.
Inclusion of new biotechnology and biosynthetic and agro-ecological approaches	It is not clear from the mission objectives if we can potentially include new technologies, which are or have been developed, when defining key actions for footprint development and policy recommendations. This should include changes that EU can implement within its own food system to reduce its dependence on outside EU food sources.

3.8 Soil Literacy

These are the key preliminary knowledge gaps identified during the Think Tank and Barcelona Conference discussion and desk research:

1. **Absence of an agreed soil health definition:** The Soil Mission understands soil literacy strongly linked to the concept of soil health. Having a comprehensive definition of what soil health is key to determine the content of the soil literacy that we want to increase. There is a need to expand the soil health concept beyond the anthropocentric idea related to ecosystem services and the view of soil as a resource humans can benefit from.
2. **Absence of a definition about soil literacy and its components/pillars:** There is a variety of knowledge, understanding and representation of soils depending on the specific type of actors addressing it. Beyond soil sciences, different groups have different understandings of what soils are. The way in which soils come to be known, represented, and understood is diverse. Additionally, soil literacy is deeply intertwined in a variety of ecosystem services or different knowledge areas, each having a different definition of soil. Therefore, a clear definition of soil literacy and its pillars that can encompass this variety of knowledge is still needed.
3. **Lack of the evaluation of the status/baseline of soil literacy in Europe:** As we mentioned previously, our preliminary desk research indicates that currently there is a lack of studies evaluating the state of the art of soil literacy. Assessing its current status in Europe would provide a reference point for measuring progress and setting realistic goals. A baseline is needed to apply targeted interventions, supporting the development of innovative solutions and assessing the effectiveness of soil literacy related activities over time.
4. **No set of indicators to monitor soil literacy:** This knowledge gap is linked with the previous one. To effectively assess and monitor the state of the art of soil literacy, a set of indicators to track the progress on the topic is needed. Since there is no established monitoring framework in this regard, research and discussion will be needed to agree on a common set of indicators that adequately serve for this purpose.
5. **Need for integration of soil literacy/sustainability education literacy into appropriate policy frameworks and initiatives:** The focus on the topic of soil literacy has gained strength thanks to the Soil Mission. At European level, “soil literacy” is still not included in any policy frameworks or regulations, even though some reference to it can be present. It is a research need to perform an analysis of the current European policy landscape to identify potential entry points and synergies that can allow the integration of the term to benefit and support the implementation and mainstreaming of future actions related to soil literacy.
6. **Insufficient understanding in terms of co-production of knowledge mechanisms on soil literacy:** As soil literacy is a topic that still requires more discussion to obtain a consensus around its definition, soil literacy still needs to improve the understanding of the way knowledge is co-produced, shared or transferred to different target groups and actors like educators, policymakers, and practitioners to efficiently support decision-making processes. Several questions remain unanswered: What do successful approaches on knowledge co-production look like? What obstacles do they face? What are their lessons learned? As we mentioned before, projects and networks at the European level have started to do some work in collecting best practices around soil literacy; however, more research and analysis needs to be done to find patterns,

elements… that serve as valuable “templates" for educators, policymakers, or practitioners to offer proven strategies that can be adapted to various contexts.

3.9 Nature Conservation of Soil Biodiversity

Gaps in Knowledge in the Taxonomy, Ecologies, and Distributions of Soil Organisms

Unknown Taxa

Many soil taxa are simply unknown to science and yet to be described (Orgiazzi et al., 2016). Moreover, organisms in soil (faunal and microbial) are cryptic and difficult to observe without disturbing their functioning and habitat. Many microbial taxa are difficult or impossible to isolate and culture with our current methodologies. This is compounded by the differences in methods necessary to detect and quantify different soil organisms due to heterogeneity in their ecologies (ranging from water-related to truly terrestrial species), size classes (ranging from microbes to megafauna) and distributions (Decaens, 2010).

The largest challenges to the conservation of soil biodiversity are the lack of information on what species/operational taxonomic units (OTUs) of soil organisms exist (microbial and invertebrate taxa), their ecologies and life histories, and how these affect biota distributions (Table 3). Even for described species, we lack critical information on which exist in which of the wide range of habitats on Earth and why. In many cases of invertebrate taxa, specialised taxonomic expertise is needed to identify species within groups of soil animals. However, teaching basic taxonomic skills has widely disappeared from university curricula, creating the danger of existing taxonomic expertise - especially for soil invertebrates - itself going extinct.

Given the high diversity of sizes, traits, functions, and ecologies of soil fauna and microbes, it is clear that the conservation of the complex functions of these communities is as important as the communities themselves and should be taken into account in considering their protection. Due to this complexity, active restoration and conservation require attention to this complexity of species richness as well as a diversity of functions (Nielsen et al., 2011). To do this, information is needed on the ecologies, life histories, and distributions of taxa (taxonomic units as OTUs etc) or functional genes. While more is understood about communities than ever before, the understanding of the functions of some very common organisms is still lacking and this inhibits our ability to identify and protect them (Table 3).

Last, but not least, the need for development of a common definition of soil biodiversity can be agreed upon as a basis for policy development and protection (Rillig et al., 2019; FAO et al., 2020; Orgiazzi, 2022). Different definitions exist for different monitoring programs and policy organisations, however one unified definition has yet to be agreed on.

Distributions of Soil Taxa

Information on the distributions of most soil taxa is widely lacking along with available information on habitat-type suitability, soil and climate dependences, and functional properties, among others ("Niche Space” *sensu* Grinnell) (Table 3). Most studied soil taxa show significant variance in diversity across millimetres (Rillig et al., 2015), while most detailed datasets on edaphic parameters and even measurements in-situ need much larger distances to discover gradients.

Overall, there is no clear picture of how soil biodiversity is related to land use type (Table 3). Though Tsiafouli et al. (2015) did observe that increasing agricultural intensification corresponded with a lower level of soil biodiversity across Europe, evaluations across land use types showed divergent relationships between species composition of communities and richness (Wood et al. 2017) with few shared drivers. Further investigations into reasons for these differences could and should include land-use history, changes in precipitation and temperature regimes related to climate, and specific management strategies which may impact soil biodiversity, such as chemical applications (pesticides and fertilizers) and soil disturbance frequencies, among others.

Unknown Ecologies of Soil Taxa

In addition to "what" is there and where it is located, qualitative attributes of soil-dwelling taxa, i.e., their ecologies, environmental dependencies and life histories, are equally unknown at respectively appropriate taxonomic levels for identification (Table 3). In addition, the complex interactions of multiple co-occurring environmental drivers that could affect distributions or evolutionary tactics are ubiquitous, but poorly studied (Rillig et al., 2019).

Moreover, data and theory on the influence of these dependencies on small- and broad-scale distributions ("drivers") are widely lacking (Thakur et al., 2020; Eisenhauer et al., 2021), rendering conservation assessments and priorities difficult (Decaens et al., 2006). Deterministic processes, such as environmental filtering, are major drivers of local community assembly. Also, while most studies today focus on species richness, much less is known about the drivers of community dissimilarity in soil taxa across ecosystems, along with their uniqueness (e.g., endemic species, specialisation for given habitats). For instance, while disturbed habitats can show high species richness and total densities, these are often caused by "generalist species", leading to a "homogenization" of soil biodiversity and loss of gamma-diversity at the landscape scale (Gossner et al., 2016; Delgado-Baquerizo et al., 2021; Guerra et al., 2021).

Studying the ecology and life histories of individual species or organisms has long been considered "natural history" and not "innovative" science. As such, acquiring funding for such research is nearly impossible. Such information is currently based on "expert knowledge", e.g., by taxonomists, whose expertise is often at a fairly local or regional scale. This information can be derived from gradient studies, but the necessary environmental and climate metadata is widely missing from such publications. The use of information available in museum collections is essentially non-existent (Gotelli et al., 2023). Observational data on species' occurrences are currently being collated in international databases, but again the required environmental and climate metadata is often missing in uploaded datasets.

Considering such qualitative attributes of soil biodiversity during assessment of site-scale measures will vastly improve conservation of soil biodiversity at broader scales (Ciobanu et al., 2019; Zeiss et al., 2022). Filling this gap will help determine, for example, the proportion of species within a local community specifically adapted or specialised to the site/habitat as a first approximation in assessing "intact" habitats or soil health as well as land-use measures or changes, etc. This knowledge will assist in more effectively examining trade-offs between deterministic and stochastic processes in community assembly or macroecological patterns as well as between specialised biodiversity and functional diversity in assessing any anthropogenic or climate-change effects on soil biodiversity.

There are instrumental, logistical (large-scale surveys including multiple temporal points are difficult to conduct), and legal restrictions in the process of collecting data on environmental predictors what makes it near to impossible to match it with the actual distribution of soil organisms belonging to different size classes in an ecologically justified way (ISRIC, 2020). Moreover, experimental data on the response of soil taxa and their diversity to environmental predictors is patchy, biassed towards unrealistic levels of edaphic parameters change and unrepresentative for the tropics, and not directly comparable across ecosystems.

Lack of Knowledge of Threats to Soil Biodiversity

What currently understood biodiversity threats are threats to soil biodiversity? What known threats need redefined thresholds to inform conservation decisions? How do we define threats to soil biodiversity that may be overlooked in conventional conservation thinking (e.g. intentional foreign microbial inocula)?

Unknown Extinction Risks

The conservation methods and status of invertebrate and microbial soil organisms, including rare species, are almost entirely unknown and have not progressed (e.g. Decaens et al., 2008) while other aspects of soil biodiversity science have. To effectively protect soil fauna and microbial life by identifying the threats on soil fauna biodiversity, and identifying very rare/threatened, endemic, and vulnerable species, and their habitats for protection are all large knowledge gaps still to be filled (Table 3). Currently, baselines and thresholds for soil organisms comparable to those for above-ground organisms do not exist although urgently called for by policy (EEA, 2023). Red Lists for soil organisms are rare (Phillips et al., 2017; Mueller et al., 2022). Only singular studies have incorporated IUCN criteria (i.e. IUCN, 2022) for identifying threatened or endangered soil species (Marchán and Domínguez, 2022; Salako et al., 2023). However, this necessitates answers to some fundamental, yet wholly un-investigated, questions: What defines rarity for soil taxa? For instance, local abundance, habitat specificity, and/or geographical distribution can be used, but which are appropriate for the myriad of soil biota? How do we determine susceptibility to extinction when it comes to soil biota? How can we define how threatened a species is when, for example, an endemic species is known from an isolated site with no or very poor knowledge of its distribution?

To identify and have threatened species recognized, detailed functional criteria for identification of species are needed, especially in the case of species that are highly sensitive to climate shift, invasion of exotic species, etc. For example, the challenging habitat soil provides for observation makes a typical criterion such as “population size”, difficult for some soil invertebrate taxa. Moreover, current technology does not allow to fully infer rarity in the case of microbial taxa in complex habitats such as soils wherein a few grams of soils contain millions of individuals of bacteria (Table 3). Current sequencing technology is only capable of capturing a few thousand sequences, limiting any attempt to establish real abundance patterns in soil. Moreover, how can we inform standardised scales of rarity and threat with inconsistent approaches within different national boundaries? This leads to a situation where species assessed as rare of threatened at national level are not considered as such at a European level and vice versa. With this knowledge, we can identify the taxa at risk, create a preliminary list of what species or ITUs are threatened, and identify conservation practices, concrete management options, and potential sites for conservation of these. This is critical to predict the fate of soil organisms under global change and ensure their conservation.

Knowledge Gaps on Invasive Species

A corollary to the identification of rare, threatened, and endemic species is, what constitutes being invasive in regard to soil biodiversity? This has not been taken into consideration, primarily, because the directionality of invasions of microbes is difficult to determine, and we are unaware of the identity of most local and invasive soil taxa (Table 3). It is also unknown what environmental or economic damage that 'invasive' organisms can cause to soil, unlike similar studies in agricultural settings, for example. One barrier to getting at this information is, first, there is no conceptual framework to think about this and may need to be reconceptualized. Additionally, there is little way to track the origin of a present microbial ITU. Increasing the taxonomic information of our soil communities, starting with that in already vulnerable ecosystems, such as those susceptible to the increasing oscillations in heat and temperature regimes, will be critical to provide the foundation to monitor the influence of soil invasive species on the functioning and stability of our ecosystems.

Data and Methods Standardizations to Understand Trends in Soil Biodiversity

Harmonization and Standardization

One of the major problems inhibiting our capacity to develop soil conservation policies is the lack of universal standardised soil data (Table 3). Researchers use different methods to measure soil biodiversity and function, which, although valid in their local studies, do not result in comparable datasets across different regions and temporal scales. Additionally, it remains unknown if, and to what degree, the spatial and temporal resolution of the measurements of environmental parameters are adequate to the actual resolution of soil biodiversity knowledge (Eisenhauer et al., 2021; Gábor et al., 2022). Similarly, different researchers measure different processes, pools, or stocks to characterize a given ecosystem function or service (e.g., plant biomass, plant productivity, crop yield), which hampers direct comparability of data. What indicators provide substantial information on the levels of soil biodiversity and associated ecosystem functions? (Guerra et al., 2021). Developing standardised methods to quantify biodiversity and function in soil is critical if we want to grow together toward a better understanding on how to conserve soil biodiversity, and the multiple ecosystem services they provide, for the next generation.

Modern statistical analyses such as Species Distribution Modelling, General Dissimilarity Modelling and Niche-Space Modelling can overcome this gap in predicting. But it will require (1) more international data collation of observational soil-biodiversity data, including a paradigm change among researchers and funding agencies regarding 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, as well as (3) funding for 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.

Conservation and Restoration

Conservation Practices that Protect Soil Biodiversity and Multifunctionality of Soils

While we fill out critical gaps of knowledge on soil taxonomy and ecology, active management is presented as the most efficient way to indirectly conserve soil biodiversity and function. Recent work has shown that current conservation practices do not typically have positive impacts on soil biodiversity or its ecological functions (Ciobanu et al., 2019; Zeiss et al., 2022), in part, because conservation policies usually do not include the ecological importance of soils in their planning. The lack of known concrete conservation management options inhibits the effective selection of areas and management regimes that protect and enhance soils (Table 3). Soil quality and protection of soil life and its functions are only now the foci of conservation management, while those of stakeholders are historically less known (i.e. agriculture, industry) (Zeiss et al., 2022). However, because 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 species/OTUs are functioning in soils and how to affect them through management (Table 1). Filling this knowledge gap has the potential to bring about more effective management of currently protected areas to enhance soil biodiversity and its functions and more appropriate selections of protected sites in the future that take region-specific soil priorities and ecological dimensions (Guerra et al., 2020) into account. This also provides information on what combinations of management practices to evaluate on an ongoing basis (given that these will inevitably overlap in some locations) (Barrios et al., 2023).

Given that the complexity of the soil food web can promote resilience to perturbation and serve as a buffer to extremes in environmental change, expansion of functional diversity of soils, including human and animal parasite helminths, in our assessment of soils is warranted. Cross-disciplinary work (chemical analyses; molecular and morphological identification) between soil ecologists and parasitologists (human or animal parasites) are necessary. This is one of our responsibilities for the future of soil health and should be plans for current and future 'assessments' i.e. SoilBON, Global Soil Biodiversity Observatory (GLOSOB).

In the context of outcomes to engage in effective conservation practices for soil biodiversity and its associated ecosystem functions, we see multiple advances in the way conservation can be envisioned and practised, and potential conservation areas evaluated to protect soil biodiversity. For instance, soil biodiversity distribution modelling would be brought to a completely different prediction reliability level and save a lot of field sampling effort in the future to predict biodiversity and functional status of soils in response to changing environment, soil status and/or climate. This can predict sites for future conservation with a small amount of ground-truthing.

Since conservation management and site selection have typically not considered soil biodiversity and its ecosystem functions, it is still unclear how conservation affects soil biodiversity and how to adjust current conservation and restoration practices to positively impact soil biodiversity across the EU and regionally. We know that current site selections and management practices do not generally benefit soil biodiversity (Zeiss et al., 2022), but potential biodiversity-friendly management options awaiting scaling up exist (Barrios et al., 2023). What does positively affect soil biodiversity? What can we extrapolate from, for example, agricultural soil management for increased ecosystem function by increasing soil biodiversity that we can adapt for improving soil biodiversity?

Soil biodiversity also has an important role to play in the ecological restoration and engineering of sites in need of soil improvement or remediation. These include, but are not limited to, nutrient cycling and carbon storage, the sequestering and transformation of harmful compounds, structural soil engineering, and biological control (Auclerc et al., 2022). But regions across Europe have to be evaluated for what specific soil biodiversity communities and associated functions they are capable of supporting. Guerra et al. (2022) showed that, globally, areas that may rank highly in one ecological dimension may not rank highly in another. For example, areas with higher species richness were not often shown to have the highest functionality. This suggests that potential sites for conservation are not equal, nor can they be treated similarly, when considering how to improve conservation and restoration practices when targeting soil biodiversity. Effective evaluation of current practices requires knowledge of these complexities, including effects of land-use and human pressure to interpret the evaluation of current practices.

Increasing our understanding of how to improve conservation and management requires long-term studies and experiments that focus on specific techniques, such as dead wood management in forests, recognition of trees as "hot spots" of biological activity, and encouraging heterogeneous soil habitat through diversifying plant species.

Functional Diversity of Soil Life: toward new microbial-trait investigations

When considering soil biodiversity, it is necessary to also consider what aspects of soil biodiversity should be the targets of future conservation. In contrast to aboveground life, which is more easily observed and vastly more investigated, the ecosystem functions of species and, especially, ITUs, and their functions have not. This leads to the question: What aspect of soil biodiversity should be the target of conservation? While the overall diversity of taxa in soil is important in and of itself, the functional aspects of soil fauna and microbial life cannot be lost in the process of protecting taxonomic diversity. Guerra et al. (2022) revealed that species richness, community composition and the maintenance of ecosystem services are not often synonymous, and investigation into a trait-based approach to soil biodiversity conservation and restoration is largely lacking.

Table 3: Knowledge Gaps Identified by the Nature Conservation TT as of January 2024.

No	Knowledge gap	Time frame			Link to other knowledge gaps
		short	**middle**	**long**	
Taxonomy, ecology and distributions					
1	Definition of taxa / species	X			2; 4; 11
2	Species ecology, environmental dependencies and life histories	X	X		1; 3; 4; 7; 8; 9; 11
3	Functional diversity				2; 11
4	Species distribution and habitat/ecological preferences	X	X	X	1; 2; 8; 9;
5	Knowledge across land use types				
Threats to soil biodiversity					
6	Threats to soil biodiversity	X			2; 8;
7	Definition of rare species	X	X	X	2; 7; 9;
8	Identification of threatened species and extinction risk	X	X	X	2; 4; 9; 11; 13

9	Methodological limitations		X	X	7;8;
Data and method standardisations					
10	Standardisation of methods		X	X	1; 2; 3
11	Spatial and temporal resolution	X			8;
12	Data storage and digitalization needs. IPR protected data	X			
Conservation and restoration					
13	Conservation strategies	X	X		6; 8
14	Conservation framework	X			
15	Offsetting conservation for soil biodiversity		X	X	6; 13; 14
16	Conservation methods	X			13; 14
17	Restoration of soil biodiversity				13

4 Related projects and initiatives

Previous sections describe the state of the different SMOs associated to each TT, including the initial knowledge GAPs already identified. Here an overview of the previous sections' description is presented with the links the SMO have with the different projects and initiatives related to Soil Health (Table 4).

Table 4: Project and initiatives associated with the SMO and the TTs.

Projects & Initiatives	MO1	MO2	MO3	MO4	MO5	MO6	MO7	MO8	TT9*	TT10**
The project «Soil Mission Support (SMS):	X	X	X	X	X	X	X	X	X	X
The agricultural European Innovation Partnership - EIP-Agri Focus Groups.	X									
The project «PREP-SOIL (Preparing the European	X		X	X				X		X

Mission Towards Healthy Soils) »										
The project «EJP SOIL- Towards Climate-Smart Sustainable Management of Agricultural Soils.	X			X	X	X				X
The United Nations Convention to Combat Desertification (UNCCD)	X									
The project «AI4SoilHealth: Accelerating the collection and use of soil health information using AI technology to support the Soil Deal for Europe and EU Soil Observatory »	X	X		X		X				
The project «SoilO-live:	X			X						
The project Soil Health Benchmarks	X	X				X				
The EU Soil Observatory group	X									
The project «EJP-SOIL – Road4Scheme	X									
The project «MRV4SOC: Monitoring, Reporting, and Verification of Soil Organic Carbon and Greenhouse Gas Balance»	X									
The GROW Observatory: Citizen Science for Climate Action	X									
The project SOILGUARD	X					X			X	X
The project «BonaRes: Soil as a sustainable resource for the bioeconomy»	X									
The project «InBestSoil:	X									
The project «HuMus: Health Municipal Soils»	X								X	

The project «NOVASOIL: Innovative Business Models for Soil Health»	X									
The project «NATIOONS: Supporting the EU Mission 'A soil deal for Europe' across national communities	X			X						
The project «NBSOIL: Nature-Based Solutions for Soil Management»	X							X		
The project «SIEUSOIL: SINO-EU Soil Observatory for intelligent land use management»	X									
The project «SoilValues: Enhancing Soil health through Values-based business models»	X									
EcoForest		X								
ForBioFunCtioN		X								
HoilSoils		X								
The 4 per 1000 initiative		X				X	X			
Truesoil, EJP soil		X								
CarboSeq EJP soil		X								
CREDIBEL		X								
SusCow		X								
GreenMove		X								
Biomass to biogass (B2B)		X								
Soil Carbon Int. Research Consortium		X								
Lucas	X	X		X					X	
NorForSoil		X								
Monitoring soil organic carbon in forest and grassland		X								

SOS4LIFE “Save Our Soils 4 Life”			X							
URBAN-SMS			X							
ReCon Soil			X							
RECARE			X							
SOILval			X							
Information exchange platform – Towards No Net Land Take (Set up by WSP)			X							
ULYSSES “Soil Sealing Assessment and Monitoring Project			X							
Soil-X-Change				X						
TUdi project				X						
SPRINT				X						
MICOS				X						
TANIA				X						
EU Soil Observatory, Working group on soil erosion					X					
MOSAIC					X					
EUropean SEDiments collaboration (EUSEDcollab)					X					
Portuguese Soil Partnership (Parceria Portuguesa para o Solo)					X					
Solo e Água 2030					X					
SOLVO					X					
EROFIRE					X					
FAO Soils Portal and initiative						X				
Holisoils (forest)						X				
Biodiversity strategy for 2030						X				

CIRCLES (agricultural soil)						X				
UN ICP forest						X				
SoilValues						X				
FNSSA Partnership, part of the EU-Africa Union High-Level Policy Dialogue.							X			
Soils4Africa							X			
LEAP4FNSSA							X			
PRIMA partnership							X			
EU-CELAC partnership							X			
Moonshot program										
Designing Living Labs and seeks further R&I collaboration							X			
Global Soil Partnership (FAO)	X						X	X	X	
European Soil Partnership	X							X		
LOESS								X		
Convention on Biological Diversity (CBD)									X	
International Initiative for the Conservation and Sustainable Use of Soil Biodiversity									X	
Global Soil Biodiversity									X	
Global Biodiversity Information Facility									X	
Edaphobase									X	
SoilBON									X	
Digital Observatory of Protected Areas									X	
GBIF									X	

IUCN Red Lists									X	

*Conservation of Soil Biodiversity
**Climate smart agriculture

- **EJP SOIL.** Drawing on the European research community, the EJP SOIL project will develop a research strategy to provide the scientific basis for policy development related to climate-smart, sustainable agricultural land management, following an assessment of knowledge, tools and methods. At Member State level, the flow of information is ensured through National Knowledge Centres, or National Hubs.

- **Soil C and Forest management EcoForest**: Ongoing. Examining how forestry practices influence forest and guide future sustainable forest management practices and climate mitigation strategies – EcoForest: In the EcoForest-project we study the long-time effects of forestry on biodiversity (insects, fungi, bacteria) in soil and dead wood, as well as carbon storage and differences in ecosystem functions. The aim is to provide a comprehensive overview on how forestry practices influence the forest and guide future sustainable forest management practices and climate mitigation strategies. ForBioFunCtioN: ongoing, Climate change impacts species communities and the processes they govern, such as the carbon cycle. The project ForBioFunCtioN assesses these impacts and how they interact with suggested climate measures, such as forest fertilizer and biochar HoliSoils Holistic management practices, modelling and monitoring for European forest soils – is an ongoing Horizon 2020 project (May 2021- October 2025) to develop a harmonised soil monitoring framework. It identifies and tests soil management practices aiming to mitigate climate change and sustain provision of various ecosystem services essential for human livelihoods and wellbeing.

- **Agronomic practices and climate smart agriculture The 4 per 1000 initiative:** L'Initiative internationale "4 pour 1000"- Les sols pour la sécurité alimentaire et le climat (4p1000.org): It aims to show that agriculture can provide concrete solutions to the challenge posed by climate change while meeting the challenge of food security through the implementation of agricultural practices adapted to local conditions: agroecology, agroforestry, conservation agriculture, landscape management, etc.

- **Truesoil, EJP soil: (2022-2025) TRUESOIL (ejpsoil.eu):** Aim of True SOC sequestration: understanding trade-offs and dynamic interactions between SOC stocks and GHG emissions for climate-smart agri-soil management CarboSeq, EJP soil (2021-2025) CarboSeq Project aim: To estimate the feasible SOC sequestration potential taking into account technical and socio-economic constraints. CREDIBEL: Ongoing. EU soil carbon farming. Funded by the European Union. Credible is an EU-funded coordination and support action. Its main goal is to build consensus on the methodologiesthat could maximise the capacity of soils to act as carbon sinks. Organises the "1st European Carbon Farming Summit 5-6-7 March 2024. Valencia".

- **Biodiversity SusCow:** Animal health and pasture carbon dynamics in sustainability assessment of ruminant production systems - SUSCOW aims to contribute to a sustainable ruminant production based on national resources in Norway by documenting the importance of animal health on environmental impacts in ruminant production systems, using whole-farm models and life cycle assessment methodology. To reduce the environmental impacts of ruminant production systems, animal health and soil carbon sequestration are two important aspects that will be studied in this project.

- **Urbanization GreenMove (2021-2025; Norwegian research council) : Green** Move - NTNU GREEN MOVE will through the holistic approach investigate several aspects of the wicked problem of soil movement.

- **Circular economy Biomass to biogass (B2B)** (2009-1013, Norwegian research council). There is a desperate need for efficient, environmentally friendly, integrated technologies for conversion of biomass, in particular recalcitrant lignocellulosic biomass, to energy. One of the most promising biomass-derived energy-carriers is biogas. To ensure sustainability and integrate d use of the complete feedstock, the project focused on (1) water recycling and challenges associated with that, and on (2) the composition, properties and applications of the organic co-product. It was essential to use the organic co-product for soil improvement, thus contributing to production of new biomass.

- **BENCHMARKS** collaborates with stakeholders in 24 European case studies to co-develop and evaluate a multi-scale and multi-user focused monitoring framework that is transparent, harmonised and cost-effective. Underpinned by the best scientific knowledge and technologies this framework aims to provide a clear soil health index for benchmarking, using indicators that are pertinent to the objective of assessment, applicable to the land use and logistically feasible.

- **Soil Carbon Int. Research Consortium** (previously ORCASA/CIRCASA). (Ongoing). The idea to create a Soil Carbon IRC emerged during the CIRCASA project (2017-2021) together with more than 100 stakeholders and 500 scientists from around the world. It was then reinforced by the launch of the ORCaSa project in September 2022. Taking things a step further, the Soil Carbon IRC will expand its scope to cover all soils (including forests, pastures, wetlands, and urban areas…). Aided by Impact4Soil, an online platform for collecting and sharing knowledge on soil carbon, the IRC, and its partners and regional nodes aim to provide better access to research, methods and practices related to soil carbon.

- **AI 4 Soil Health**. (Ongoing) is one of a group of Horizon Europe funded projects which fit under the EU's Soil Health Mission for 2030. The consortium consists of Charities and companies from across Europe. The psroject aim at Helping the farmers and land managers of tomorrow by providing new tools to measure soil health without the need for laboratories. Using artificial intelligence to monitor and predict soil health for farmers and growers across Europe.

- **LUCAS** In 2009, the European Commission extended the periodic Land Use/Land Cover Area Frame Survey (LUCAS) to sample and analyse the main properties of topsoil in 23 Member States of the European Union (EU). This topsoil survey represents the first attempt to build a consistent spatial database of the soil cover across the EU based on standard sampling and analytical procedures, with the analysis of all soil samples being carried out in a single laboratory. Approximately 20,000 points were selected out of the main LUCAS grid for the collection of soil samples. A standardised sampling procedure was used to collect around 0.5 kg of topsoil (0-20 cm). The samples were dispatched to a central laboratory for physical and chemical analyses.

- **NorForSoil** is a platform for researchers and stakeholders involved with monitoring of forest soil in the Nordic and Baltic countries. We will explore possibilities to harmonize national soil monitoring data and methodology across borders for integrated analysis, including existing data, future data collected with current methods as well as the potential for development and harmonization of future monitoring design and methods. The short-term focus is on forest soil organic carbon (SOC), but the potential for including other soil properties in analyses will also be outlined. NorForSoil includes eight Nordic and Baltic countries (nine research institutes) and is, via an ongoing PhD study, linked also to the national soil monitoring in Canada.

- **Monitoring soil organic carbon in forests and grasslands:** soil contains vast amounts of carbon. The amount of carbon stored in the soil in boreal forests is greater than that which is stored in trees and other vegetation. There is also a great amount of carbon stored in grasslands. Changes in the carbon stores are affected by climate change and also by the management of forests and grasslands. However, there is little data on the amount of soil carbon stored in Norwegian soils and there are no historic data that describe the development in Norwegian SOC stores over time.

- **SOS4LIFE "Save Our Soils 4 Life**" (https://www.sos4life.it/), Life project. It was a demonstration project aimed to contribute to the enforcement of European orientations about soil protection and urban regeneration at the municipal level in Emilia Romagna in Italy (time period 2016-2019).

- **PREPSOIL "Preparing for the 'Soil Deal for Europe' Mission**" (https://prepsoil.eu/). It facilitates the deployment of "A Soil Deal for Europe" mission across European regions, by helping key players to reduce soil degradation, while increasing soil awareness and soil literacy (time period 2022-2025).

- **SMS "Soil Mission Support: Towards a European research and innovation roadmap on soils and land management**" (https://cordis.europa.eu/project/id/101000258). The project developed a set of research and innovation activities leading to an effective framework for action in Europe and globally in the fields of soil health and land management (time period 2020-2022).

- **ReCon Soil** (https://www.claire.co.uk/projects-and-initiatives/recon-soil), Interreg project. It studied the potential reuse of surplus materials from the construction industry (time period 2021-2023).

- **URBAN-SMS "Urban soil management strategy"** (https://keep.eu/projects/5537/Urban-Soil-Management-Strate-EN/). It strived to develop a comprehensive soil management strategy for municipalities to consider the value of soils and their different functions within the urban planning process (time period 2007-2013).

- **RECARE "Preventing and Remediating degradation of soils in Europe through Land Care"** (https://www.recare-hub.eu/recare-project). It RECARE project brought together a multidisciplinary team of 27 different organisations to find ways of assessing the current threats to soils and finding innovative solutions to prevent further soil degradation across Europe, among which they also focused on soil sealing (time period 2013-2018).

- **SOILval** (https://www.soilver.eu/news/project-soilval-recognising-soil-values-in-land-use-planning-systems/). The aim of SOILval was to enable better recognition of the value of soils in the context of land planning and development in France and Wallonia. The SOILval project aimed specifically to evaluate over a period of one year (2020-2021) how the concept of soil value is recognised and or integrated in France and Wallonia in legal instruments and planning decision-making processes. The project also investigated how operational solutions for soil refunctionalisation could contribute to a better consideration of soil quality. The project is linked to SOILveR (https://www.soilver.eu/), a self-financed platform aimed to respond to the need for integrated soil and land research and knowledge exchange in Europe. The partners acknowledge the added value of coordinating, co-funding, and disseminating cross-border soil and land management research (ongoing).

- **"Information exchange platform - Towards No Net Land Take"** set up by WSP to support the European Commission. As part of the project, they are setting up an open exchange of information on local/regional/national policies, measures, and initiatives, to identify and appraise best practices. This will help the Commission with future policies and guidelines on the topic (ongoing).

- **ULYSSES "Soil Sealing Assessment and Monitoring Project"** (https://www.ulysses-project.org/products/), a Mediterranean Regional Initiative by ESA. It aims to provide specific products related to soil sealing presence and degree over the Mediterranean coastal areas by exploiting EO data with an innovative methodology capable to optimise and scale-up their use with other non-EO data (ongoing).

- **Soil-X-Change.** The Soil-X-Change initiative aims to promote knowledge exchange and cooperation on sustainable soil use and management. It connects farmers, policy makers, projects, and initiatives to accelerate innovation and promote the implementation of sustainable solutions.

- **TUdi project** aims at improving soil health by restoring or maintaining good soil quality for food production. The project contributes to the development of healthy and productive agricultural ecosystems, which are among the UN's priority development goals for 2030. To this end, TUdi will draw on 15 research institutes and SMEs from around the world, a network of 42 collaborating organisations, 66 long-term experiments and monitored farms in participating countries.

- **SPRINT**. It aims to develop a Global Health Risk Assessment Toolbox to assess impacts of Plant Protection Products (PPPs) on environment and human health and to propose several transition pathways. The SPRINT project will make an internationally valid contribution to assess integrated risks and impacts of pesticides on environment and human health, both at regional and European level. SPRINT will inform and accelerate the adoption of innovative transition pathways towards more sustainable plant protection in the context of a global health approach.

- **SOIL O-LIVE.** The olive tree plays a crucial role in oil production in the Mediterranean region. However, olive growers face challenges such as intensive agriculture practices, land degradation, biodiversity loss, and functionality reduction. The SOIL O-LIVE project, funded by the EU, aims to address these challenges through various multidisciplinary and interdisciplinary projects. The project will assess the environmental condition of olive grove soils on a large scale in the major Mediterranean olive production areas. SOIL O-LIVE will examine how pollution and land degradation affect olive groves' soils, investigate the connection between soil health and the quality and safety of olive oil, implement effective soil amendments and ecological restoration practices, and establish strict ecological thresholds for healthy European olive groves.

- **MICOS.** A healthy soil, a healthy plant. In collaboration with the industry, the research team is striving to establish sustainable, healthy agriculture. This project investigates whether and to what extent microplastics are present in the soil, and if they affect soil and plant health. The researchers involved are investigating whether our agricultural soils contain the solution we're looking for: plastic-degrading bacteria or fungi, which are used to break down (micro)plastics.

- **Natioons.** Natioons is supporting the EU Mission "A Soil Deal for Europe" across national communities The project act as a messenger for the EU Mission Soil through multiple activities: Raising awareness nationally and regionally, providing access to capacity-building materials, addressing regional soil needs through LL setups and fostering matchmaking for LL clusters.

- **TANIA.** It aims to create new business opportunities for enterprises promoting nanoremediation products and services. Raise awareness on contamination of EU natural heritage, its effects, and the potential of nanoremediation. Promote long-term, sustainable regional development and competitiveness: better environmental conditions, consequent improvements to health and increased business opportunities.

5 Next Steps

As mentioned, this deliverable is the first synthesis of the work each TT developed during 2023 in SOLO. It comprises the scanning, population and kick off for every TT, starting with the main definitions and common ground to start the transdisciplinary R&I Roadmaps. Collaboratively, the TT and the project partners worked on the main points to be discussed and integrated (summarized in D2.1 and D2.2). Then several online meetings were held by each TT and with the TT leaders in parallel steering and sharing that process which started last year. Initial state of the art through a scoping document has been drafted and discussed at three layers: i) internally by the TT members, ii) among TT and SOLO partners through a participatory meeting in Barcelona in December 2023 and, iii) in an open review through ARPHA repository.

A similar process will be developed for 2024 (Figure 5) following the project directives (Figure 2).

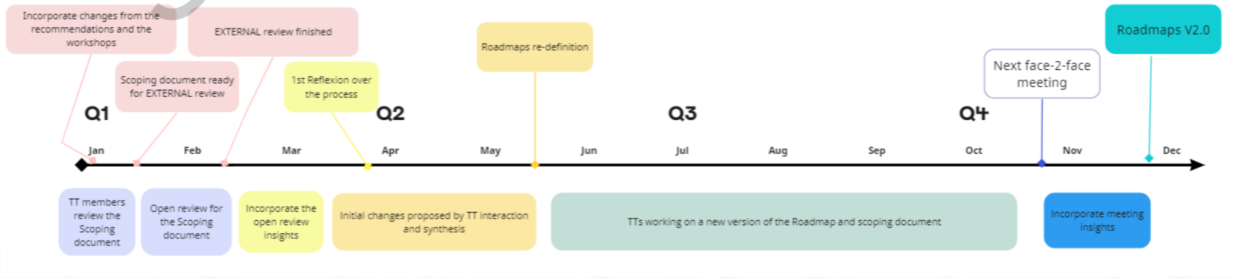

Figure 5: Timeline for the TTs activities to be performed during 2024

As explained in section 1.2 of this deliverable, the iterative and participative process of the roadmaps is the backbone of SOLO. Therefore, here the timeline and the next steps for the TTs are included. In this sense, this year the open review process and the insights from the last year reflexion will take place at the first part of the year. Second, all the needs and challenges detected will be addressed prior and during the consortium meeting in April. Third, this process will be shared with the key stakeholders for every TT. In parallel, the WPs related to an overall synthesis, Regional Nodes and drivers will interact with the TTs for a re-definition of the SOLO R&I Roadmaps. Fourth, all those considerations will be reflected into a new version of the documents drafted. Fifth, a face-2-face interactive meeting with the key stakeholders of all the TTs will take place. Finally, all the insights will be incorporated into the new version of the Roadmap.

6 Acknowledgements

The present deliverable, and all the multiple versions of drafts developed by each Think Tank related to the GAPs and the state-of-the-art of each topic/objective are accomplish as a huge collective task that counted with a generous work from many people of different expertise, backgrounds, ages and fields.

Therefore, we want to not only acknowledge but remarkably recognise and credit all those who contributed throughout the SOLO project process making it outstand. Huge thank to all the stakeholders of each TT that participate and contribute to the internal discussions, multiple drafts and virtual meetings are a backbone for the consecution of this deliverable.

Special recognition of those who openhanded participated in the Barcelona face-to-face meeting in December. The inputs throughout discussions and dynamics performed within and among TTs and other partners from the consortia were extremely valuable.

Hoping it is a starting point and we can continue with these collaborations during the roadmapping process we thank you all again.

7 References

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Appendix I

The relationship between the EU Soil Monitoring Law proposal and the Figure 1 in the scoping

Monitoring requirements of SML are set in the Annexes. The table below shows the links between Figure 1 and the Annexes of the SML

Table 1 of Appendix I Links between Figure 1 and Annexes of SML

Figure 1	Annexes of SML
1) Soil pollution	**Annex I** Soil Descriptors, Criteria for Healthy Soil Condition, and Land Take and Soil Sealing Indicators
2) Effects of pollution	**Annex II** Methodologies **Annex VI** Phases and Requirements of Site-specific Risk Assessment **Annex VII** Content of Register of Potentially Contaminated Sites and Contaminated Sites
3) Stakeholders having impact on pollution or being impacted by pollution	**Annex IV** Programmes, Plans, Targets and Measures referred to in Article 10
4) Solutions to mitigate Soil Pollution	**Annex III.** Sustainable Soil Management Principles **Annex V** Indicative List of Risk Reduction Measures, **Annex VI** Phases and Requirements of Site-specific Risk Assessment

Table 2 of Appendix I shows which part of Annex I (Soil Descriptors, Criteria for Healthy Soil Condition, and Land Take and Soil Sealing Indicators) is relevant to PRTT. (Annex I makes links between soil degradation, soil descriptors, soil health criteria and who sets the criteria: Part A – by the EU, Part B – by the member states, Part C – without criteria)

Aspect of soil degradation	**Soil descriptor**	**Criteria for healthy soil condition**	**Land areas that shall be excluded from achieving the related criterion**
Part A: soil descriptors with criteria for healthy soil condition established at Union level			
Salinization	Electrical Conductivity (deci-Siemens per meter)	< 4 dS m^{-1} when using saturated soil paste extract (eEC) measurement method, or equivalent criterion if using another measurement method	Naturally saline land areas; Land areas directly affected by sea level rise
Part B: soil descriptors with criteria for healthy soil condition established at Member States level			
Excess nutrient content in soil	Extractable phosphorus (mg per kg)	< "maximum value"; The "maximum value" shall be laid down by the Member State within the range 30-50 mg kg^{-1}	No exclusion

Soil contamination	- concentration of heavy metals in soil: As, Sb, Cd, Co, Cr (total), Cr (VI), Cu, Hg, Pb, Ni, Tl, V, Zn (μg per kg) - concentration of a selection of organic contaminants established by Member States and taking into account existing concentration limits e.g. for water quality and air emissions in Union legislation	Reasonable assurance, obtained from soil point sampling, identification and investigation of contaminated sites and any other relevant information, that no unacceptable risk for human health and the environment from soil contamination exists. Habitats with naturally high concentration of heavy metals that are included in Annex I of Council Directive 92/43/EEC3 shall remain protected.	No exclusion

Part C: soil descriptors without criteria

Aspect of soil degradation	**Soil descriptor**
Excess nutrient content in soil	Nitrogen in soil (mg g^{-1})
Acidification	Soil acidity (pH)
Loss of soil biodiversity	Soil basal respiration ((mm^3 O_2 g^{-1} hr^{-1}) in dry soil Member States may also select other optional soil descriptors for biodiversity such as: - metabarcoding of bacteria, fungi, protists and animals; - abundance and diversity of nematodes; - microbial biomass; - abundance and diversity of earthworms (in cropland); - invasive alien species and plant pests