Soils SOLO for Europe

Integration, synergies and trade-offs across roadmaps and Mission objectives

Deliverable D4.2

27 November 2025

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SOLO
Soils for Europe

Funded by the European Union

Prepared under contract from the European Commission

Grant agreement No. 101091115
Horizon Europe Research and Innovation and other actions to support the implementation of a mission in the area of Soil health and Food

Project acronym: **SOLO**
Project full title: Soils for Europe
Start of the project: December 2022
Duration: 5 years
Project coordinator: Prof. Dr Carlos António Guerra

Deliverable title: Integration, synergies and trade-offs across roadmaps and Mission objectives
Deliverable n°: D4.2
Nature of the deliverable: Report
Dissemination level: Public

WP responsible: WP4
Lead beneficiary: NIOO

Citation: Koorneef, G.J., Nóvoa, T. Chowdhury, S., Dönitz, E.J., Enríquez, S., Farfan, M.A., van der Putten, W.H. (2025). *Integration, synergies and trade-offs across roadmaps and Mission objectives*. Deliverable D4.2 EU Horizon 2020.

Due date of deliverable: M36
Actual submission date: Month 36

Deliverable status:

Version	Status	Date	Author(s)
0.1	Draft	19-05-2025	Guusje Koorneef (NIOO)
1.0	Draft	21-05-2025	Guusje Koorneef (NIOO) Wim van der Putten (NIOO)
2.0	Draft	05-11-2025	Guusje Koorneef (NIOO) Wim van der Putten (NIOO)
3.0	Draft	13-11-2025	Guusje Koorneef (NIOO) Shaswati Chowdhury (Zalf)
4.0	Draft	17-11-2025	Guusje Koorneef (NIOO) Wim van der Putten (NIOO)
5.0	Draft	18-11-2025	Guusje Koorneef (NIOO) Teresa Nóvoa (Evora)
6.0	Draft	19-11-2025	Guusje Koorneef (NIOO)

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7.0	Draft	24-11-2025	Guusje Koorneef (NIOO) Wim van der Putten (NIOO) Teresa Nóvoa (Evora)
8.0	Draft	27-11-2025	Guusje Koorneef (NIOO) Wim van der Putten (NIOO) Teresa Nóvoa (Evora) Shaswati Chowdhury (Zalf) Ewa Dönitz (Fraunhofer) Monica Farfan (iDiv) Sahsil Enríquez (LEITAT) Cathy Béatrice Kurz Besson (Coimbra)

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Executive summary

Introduction project SOLO

Healthy soils are the basis for sustainable life on Earth, yet over 60% of soils in Europe are degraded. The Soil Strategy of the European Union, therefore, aims to restore all soils in Europe by 2050. Soils for Europe (SOLO) investigates what knowledge and innovation are needed to achieve this goal by developing transdisciplinary roadmaps that support structuring the policy agenda for future soil research and innovation. The basis of these roadmaps is knowledge gaps that are prioritized by a wide audience of stakeholders, end users, and experts as most urgent for improving soil health in Europe. In order to obtain these inputs, SOLO has organized Think Tanks, Regional Nodes, and Soil Weeks, and provides reports that are exposed to open review processes.

In the roadmaps, actions suggest how the identified knowledge gaps should be solved, and bottlenecks describe what could hinder taking those actions. The roadmaps align to all Soil Mission Objectives, each one iteratively co-constructed by a transdisciplinary Think Tank. Through Regional Node workshops, SOLO assesses the different needs for research and innovation across different European regions. Regional Nodes develop local research and innovation roadmaps for different land uses in four contrasting European regions. Further regional inputs are acquired during the Soil Week events that are organized by all SOLO partners in 12 countries.

The current SOLO deliverable 4.2 presents the overarching roadmap resulting from integrating the outputs of the SOLO Think Tanks, Regional Nodes and Soil Weeks. This overarching roadmap contains:

1) Quantitative tables that summarize and characterize the different elements of the Think Tank roadmaps: the knowledge gaps, actions and bottlenecks.
2) The identified synergies and trade-offs across Soil Mission Objectives.
3) Strategies to identify leverage points in overcoming implementation bottlenecks.
4) The identified synergies and trade-offs across regions.
5) A conceptual framework that postulates the broader societal changes that are required in the transition towards a more sustainable use of soils in Europe.
6) Conclusions leading to four strategies to overcome potential overlaps in actions to solve knowledge gaps of different Mission Objectives.

1. Quantitative summary of the Think Tank roadmaps

The nine Think Tank roadmaps consisted of in total 86 prioritized knowledge gaps, of which most required generating new knowledge. About a quarter of the prioritized knowledge gaps mainly required developing mechanisms for a more effective implementation of already existing knowledge. In total, the Think Tank roadmaps identified 235 actions, of which the majority were classified as to be both research and innovation actions. The remaining actions were equally characterized to be mostly research (58 actions) or innovation (also 58 actions). In total, 304 bottlenecks have been identified.

2. Synergies and trade-offs across Soil Mission Objectives

Resources that allow executing research and innovation actions can only be spent once. Synergies therefore occur when a single research or innovation action may help to solve multiple knowledge gaps across various Mission Objectives. Trade-offs then arise when addressing one

knowledge gap limits the ability to address a knowledge gap of another Mission Objective, so that that selecting one research or innovation action comes at the expense of others. We used the nine Think Tank roadmaps to find the synergies and trade-offs across Mission Objectives in an objective and quantitative manner. We combined bottom-up and iterative co-construction approaches to find overarching knowledge gaps by carrying out a so-called 'thematic synthesis' (Barnett-Page and Thomas, 2009). This synthesis resulted in nine overarching knowledge gaps:

1) Drivers of soil health.
2) Sustainable land and soil management.
3) Soil monitoring.
4) Policy and land use planning.
5) Livelihood, soil stewardship and communication.
6) Impact of soil health on society.
7) Natural soil processes.
8) Economy.
9) Research requirements.

We subsequently allocated the individual knowledge gaps of the Think Tank roadmaps to one or multiple of these overarching knowledge gaps. Of these overarching knowledge gaps, there were four that appear especially promising for developing synergistic research and/or innovation actions:

1) Actions aimed at the 'drivers of soil health' were linked to numerous knowledge gaps of all Mission Objectives, with ≥ 40% of the knowledge gaps of each Think Tank roadmap related to this theme.
2) Actions aimed at 'consequences of soil health for human society' are also relevant for all Mission Objectives, although this subject did not turn out to be a dominantly recurring theme.
3) Actions aimed at policy innovations could benefit all Mission Objectives, since half of the knowledge gaps in each Think Tank roadmap was somehow related to 'Soil monitoring'. In addition, 'Policy and land use planning' was also relevant for most Mission Objectives, except for *Soil literacy* and *Soil biodiversity*.
4) Actions aimed at developing 'sustainable land and soil management' strategies are highly relevant for all Mission Objectives, with 30-80% of the knowledge gaps predominantly focusing on this theme, except for *EU global footprint on soils.*

Finally, it appeared that for all Mission Objectives it does not only matter *what* knowledge is developed or applied, but also *how* this knowledge should be developed or applied. In 90% of the knowledge gap descriptions information has been provided on how the specified knowledge gaps should be solved.

The strongest trade-off was observed for solving knowledge gaps on *EU global footprint on soils* and *Soil literacy* on the one hand and the other Mission Objectives on the other. Therefore, solving all knowledge gaps in these two categories of Mission Objectives will require sufficient allocation of specific funding to each of the separate knowledge gaps, as gaps of these Mission Objectives are not expected to be solved in the suggested synergistic research and/or innovation actions.

3. *Strategies to identify leverage points in overcoming implementation bottlenecks*

We identified six overarching bottlenecks from the 304 bottlenecks present in all Think Tank roadmaps in a similar manner as for the overarching knowledge gaps. These overarching bottlenecks are:

1) Resource limitations.
2) Complexity and/or context-dependency.
3) Lack of standardization or absence of a monitoring system and/or research methods.
4) Inadequate knowledge network among soil stakeholders.
5) Inadequate attitude, focus and/or limited awareness of the importance of soil health.
6) Inadequate policy and/or governance.

The three most frequently occurring types of overarching bottlenecks were related to the first three list items.. All overarching bottlenecks turned out to apply to seven or more Mission Objectives, pointing at strong synergism and relatively few trade-offs in allocating resources to solving main bottlenecks. Contrary to the need for specific funding to solve knowledge gaps specific to the Mission Objectives *EU global footprint on soils* and *Soil literacy*, this did not seem to be the case for the Mission Objective-specific bottlenecks.

We found out that some bottlenecks were blocking the solution of a wide range of knowledge gaps, whereas other bottlenecks were less impacting. More impacting bottlenecks show that soil health would substantially benefit from the developpement of a more suitable, well-standardized monitoring system and adequate research methods. Furtermore, overcoming resource limitations beyond European funding forms another leverage point, for instance via improving soil education, increasing the efficiency of the allocation of existing resources, and reducing institutional barriers.

4. *Synergies and trade-offs across regions*

Synergies and trade-offs across regions were identified from the knowledge gaps collected during the Soil Week events and Regional Node workshops in 4 and 12 different countries, respectively. Synergies occur when a single research or innovation action may help to solve multiple knowledge gaps across various regions. Trade-offs occur when addressing knowledge gaps from one region limits the ability to solve knowledge gaps in another region. The size of a region depends on its definition, and can range from local (kilometre-scale) to EU-wide continental scale. In SOLO, we used the Regional Node workshops and Soil Week events to collect regional inputs at three different regional scales:

- A region of appr. 30x30 km, the scale at which the Regional Nodes operate.
- A country, the scale at which the Soil weeks were mostly operating.
- A European macro-region, by aggregating the results of the Soil Weeks at country level into four EU macro-regions:
    - South: Spain, Portugal, Italy, Greece.
    - North: Finland, Norway, Sweden.
    - East: Hungary, Bulgaria.
    - West: Netherlands, Belgium, Germany.

Soil Week events have so far resulted in the identification of 259 knowledge gaps, and Regional Node workshops in 132 knowledge gaps. The audience and diversity of the Soil Week events was wider compared to the Regional Node workshops. The Regional Nodes workshops were also developed in an iterative way, with each workshop building on the previous one, which was not the case for Soil Week events. This different methodology was reflected in an observed trade-off

between the size of the reached audience on the one hand and the thoroughness of the collected inputs on the other hand.

To assess synergies and trade-offs across regions, we allocated the identified knowledge gaps from the Soil Week events and Regional Nodes to the nine overarching knowledge gaps identified from the Think Tank roadmaps. We performed this analysis separately for Regional Nodes and Soil Weeks given their different setup, and grouped the results by the different regional scale (region, country, macro-region).

Integrating all results from the Regional Node workshops and Soil Week events with the results from the Think Tanks roadmaps resulted in five overarching knowledge gaps that provide opportunities for developing synergistic research and/or innovation actions:

1) All overarching knowledge gaps were -although to a variable extent- relevant to all macro-regions of the Soil Weeks. Addressing multiple Mission Objectives into synergistic overarching research and/or innovation projects, for instance via the nine overarching knowledge gaps (see *2. Synergies and trade-offs across Soil Mission Objectives)*, is therefore promising for the whole of Europe.
2) Actions aimed at solving knowledge gaps for 'sustainable land and soil management' were relevant for all four Regional Nodes, all twelve countries organizing a Soil Weeks, and all four macro-regions based on the Soil Weeks results. This overarching knowledge gap was also highly relevant for all Mission Objectives, except for *EU global footprint.*
3) Actions aimed at 'Soil monitoring', and to a slightly lesser extent 'Policy and planning' were relevant for both the four Regional Nodes and the macro-regions, as well as for most countries that organized Soil Week event, except for Germany and Sweden. This overarching knowledge gap was also highly relevant for all Mission Objectives.
4) Actions aimed at 'Livelihood, soil stewardship and communication' were relevant for all Regional Nodes, Soil Weeks countries, and Soil Week macro-regions. This overarching knowledge gap was especially relevant for *Soil Literacy*, *Desertification and land degradation* and *Soil erosion*, but less so for the other Mission Objectives.
5) Actions aimed at 'Drivers of soil health' were the most relevant for all macro-regions and countries of the Soil Week events. Those actions were also the most important for all Mission Objectives. However, this overarching knowledge gap appeared to be less relevant for the Regional Nodes compared to the other regional scales.

Actions aimed at solving knowledge gaps for 'Economy' appeared to be the least relevant for Regional Nodes, countries, and macro-regions and for all Mission Objectives. No strong trade-offs were identified across regions or countries. At the macro-region scale, however, the Northern macro-region seemed to potentially form a trade-off with other macro-regions: 'Drivers of soil health' and the 'Impact of soil health on society' gaps were much more relevant in the North than in the other macro-regions, whereas gaps on 'Policy and land use planning', and 'Livelihood, soil stewardship and communication' were less relevant. The synthesis of all results from Think Tanks, Regional Nodes, and Soil Weeks leads the identification of three overarching knowledge gaps with a high potential synergism and high relevance for solving knowledge gaps in all Mission Objectives *and* all for all spatial sizes, from regional nodes to countries and EU-macro-region. Those overarching knowledge gaps are:

1) Sustainable land use and soil management.
2) Soil monitoring.
3) Policy and land planning.

5. *A conceptual framework on the required societal changes to improve soil health status in EU*

We used recent scientific literature to develop a conceptual framework that specifies and structures the societal transformations needed to improve soil health in the EU. The framework also includes a timeline for action and formulation of the expected outputs and outcomes, supporting the integration of the Think Tank roadmaps, the Regional Nodes, and the Soil Weeks. The required societal changes have been described for the four major land-uses in the EU: agricultural, urban-industrial, forestry and natural soils. The changes are further specified by:

1) The **scale**, representing whether the entire society or only a particular societal segment should be transformed.
2) The **rate,** representing at which speed the changes are expected to evolve after taking the required actions.
3) Which **elements** of society especially need to be changed: culture, structures, practices.
4) What **actors** are key for realising the proposed changes.

The conceptual framework integrates novel insights into decision-making processes in order to show how changes may be realized, which actors need to take decisions, and at which scales and levels the decisions need to be taken. In the future, SOLO roadmaps will be linked to this framework.

6. *Conclusions: Strategies to overcome overlaps in actions in solving knowledge gaps*

We propose four strategies to further enhance efficiency and avoid overlaps in solving knowledge gaps of different Mission Objectives:

1) Combine multiple Mission Objectives into individual research or innovation actions.
2) Consider the entire societal system affecting soil health when formulating research topics for transformative change.
3) Include indicators of all Mission Objectives into one soil monitoring framework.
4) Include the expected knowledge and innovation delivery of running projects in the agenda for soil research.

List of abbreviations

EU	European Union
KG	Knowledge Gap
BN	Bottleneck
SOLO	Soils for Europe project
TT	Think Tank

1 Introduction

Soil health is defined by the European Commission as “The physical, chemical and biological condition of the soil determining its capacity to function as a vital living system and to provide ecosystem services” (*Proposal for a directive of the european parliament and of the council on Soil Monitoring and Resilience (Soil Monitoring Law)*, 2023). Soil health is critical for environmental sustainability and life on Earth, however, currently, over 60% of European soils are degraded (EUSO Soil Health Dashboard (Join Research Centre, 2025)). Therefore, the Soil Strategy has been established to restore health of all soils in Europe by 2050. To further support this ambition,The EU Soil Mission “a Soil Deal for Europe” serves to implement this Strategy by delivering science-based innovation, data, and solutions that feed into policy actions. In this continuum, the EU project SOLO enhances the impact of the Soil Mission by developing holistic and transdisciplinary roadmaps for future EU soil research and innovation.

The core of SOLO roadmaps is formed by the prioritized knowledge gaps for improving EU’s soil health. The roadmaps suggest actions to solve the knowledge gaps and identify the bottlenecks that may hinder those actions. The roadmaps align with each of the Soil Mission Objectives and are co-constructed by transdisciplinary Think Tanks in an iterative and multi-actor approach (SOLO Outlook 2025). In addition, regional research and innovation roadmaps have been developed by Regional Nodes for different land uses in four contrasting regions in Sweden, Portugal, The Netherlands, and Hungary. Further regional inputs are delivered by Soil Week events in the twelve member states of the SOLO partners (SOLO Outlook 2025). This deliverable synthesizes the outputs of the SOLO Think Tanks, Regional Nodes and Soil Weeks into one overarching roadmap by both horizontal and vertical integration (Figure 1):

1) “Horizontal integration” of research and innovation priorities across the Soil Mission Objectives.
2) “Vertical integration” of research and innovation priorities across regions.

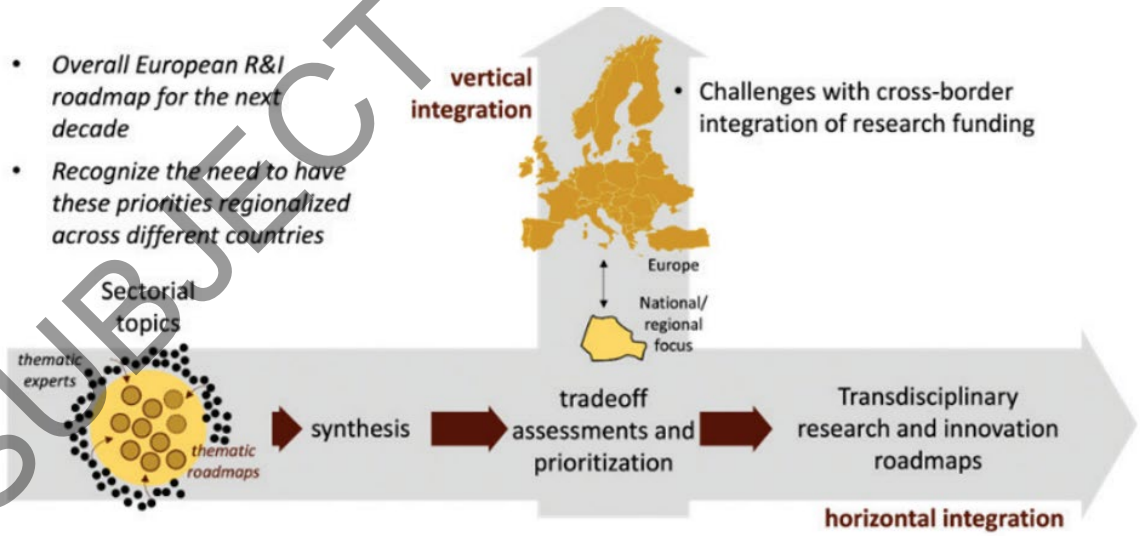

Figure 1. In SOLO, the integration of the transdisciplinary research and innovation roadmaps is conceptualized both horizontally and vertically. The horizontal integration assesses the synergies and trade-offs for solving knowledge gaps across different Soil Mission Objectives. The vertical integration assesses the synergies and trade-offs for solving knowledge gaps across different regions of the EU. (Figure from: SOLO Outlook 2025).

To support the integration of results across SOLO activities and Work Packages, WP4 has developed a workflow that details how, when and what information circulates (Figure 2). The workflow constitutes a mechanism for the regionalization of the Think Tanks' roadmaps, as it facilitates the continuous and fluid integration of regional input in the roadmaps throughout the course of the project. The workflow is described in detail in Deliverable D4.6, but it is worth reminding what role is played in it by the different activities:

- **Think Tanks** (WP2): analyse in-depth what is needed to improve each Mission Objective in practice, by identifying and prioritising knowledge gaps, bottlenecks and actions.
- **WP3**: identify drivers that induce changes both for soils and land management across land uses and countries.
- **Regional Nodes** (WP4): assess which knowledge gaps are the most urgent to overcome and what are the synergies and trade-offs between Mission Objectives within each of the 4 regions.
- **Soil Weeks** (WP4): complement and validate information in 12 national contexts by broadening the audience.

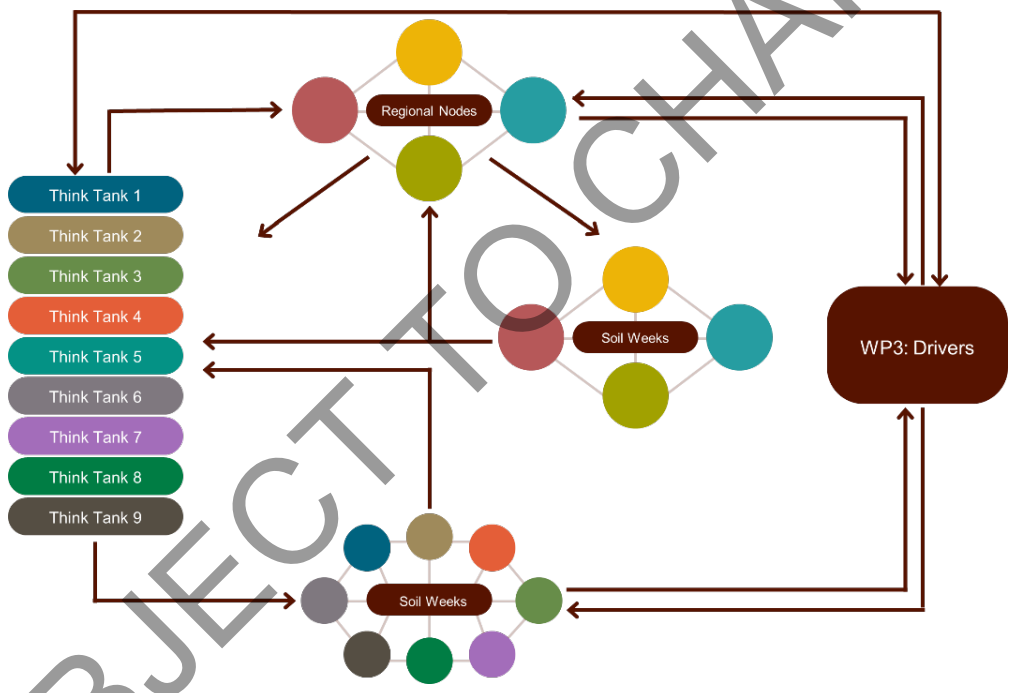

Figure 2. Workflow between Think Tanks, Regional Nodes, Soil Weeks and WP3

Integrating the outputs of Think Tanks, Regional Nodes and Soils Weeks, this deliverable 4.2 presents:

1) Quantitative tables that characterize and summarize the different elements of the Think Tank roadmaps: the knowledge gaps, actions and bottlenecks.
2) The identified synergies and trade-offs across Soil Mission Objectives and across EU regions.
3) Strategies to identify leverage points in overcoming implementation bottlenecks.
4) Strategies to overcome potential overlaps in solving knowledge gaps.
5) A conceptual framework that postulates the broader societal changes required for the transition towards healthier soils in Europe, including who should take actions and what is

the expected timeline of the required changes. Ultimately, SOLO roadmaps will be embedded in this theoretical framework.

The SOLO overarching roadmap will be further updated by integrating new information from Think Tanks, Regional Nodes and Soil Weeks according to an iterative process, the latest results of which are reported in this deliverable 4.2. The intention of the overarching roadmap is thus to develop an effective agenda for funding research and innovation initiatives as a resource for policy-makers, officials, and those interested in soil health priority-areas across Europe.

2 Quantitative summary tables of Think Tank roadmaps

We use the term 'Think Tank roadmaps' to refer to all roadmaps produced individually by the nine Think Tanks, each focusing on one specific objective of the Soil Mission plus the additional one on the conservation of soil biodiversity. This section synthesizes the numbers and specifications of the different roadmap elements (i.e., knowledge gaps, actions, bottlenecks) produced thus far by the nine different SOLO Think Tanks. We only considered the

2.1 Specification and number of knowledge gaps

SOLO distinguishes between two different types of knowledge gaps that target the science-society interface:

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

Particularly knowledge development gaps often have elements of knowledge application gaps, since new knowledge needs to be both generated *and* applied. Think Tanks were therefore asked to characterize their knowledge gaps based on where the current gap is *primarily* situated: in generating new *or* applying already existing knowledge. Think Tanks classified a knowledge gap to both types only if the balance was even. During the stakeholder meeting in Sofia (November 2024), each Think Tank was asked to vote on which ten knowledge gaps should be prioritized over the others (see D2.4). This prioritization exercise was repeated in a subsequent online stakeholder meeting (D4.2), resulting in 10 prioritized knowledge gaps per roadmap. Two think tanks deviated from this: (1) the Think Tank on *EU global footprint on soils* only identified four knowledge gaps in total, and (2) the Think Tank on *Soil structure* split two knowledge gaps after the prioritization exercise, resulting in a total of 12 knowledge gaps (Table 1).

Approximately half of the prioritized knowledge gaps mainly required generating new information or understanding (49 of 86 gaps, Table 1). About a quarter of the prioritized knowledge gaps mainly required developing mechanisms for a more effective implementation of already existing information or understanding (22 of 86 gaps, Table 1). Relatively few knowledge gaps relied on a precise balance between generating and applying new information (15 of 86 gaps, Table 1).

Table 1. The number of prioritized knowledge gaps that each Think Tank has identified in its roadmap. These prioritized knowledge gaps are further classified as knowledge development gaps (KDG), knowledge application gaps (KAG), or an equal share of both categories (both KDG and KAG). In the Table, total and specific numbers of knowledge gaps are shown per roadmap, each developed by one of the nine Think Tanks.

Think Tank roadmap	Total of prioritized knowledge gaps	Knowledge development gap (KDG)	Knowledge application gap (KAG)	Equally KDG and KAG
EU global footprint on soils	4	2	2	0
Desertification and land degradation	10	7	3	0
Soil biodiversity	10	8	1	1
Soil erosion	10	6	4	0
Soil literacy	10	6	4	0
Soil organic carbon	10	6	4	0
Soil pollution	10	0	1	9
Soil sealing and reuse urban soils	10	9	1	0
Soil structure	12	5	2	5
Total	**86**	**49**	**22**	**15**

The classification of the different types of knowledge gaps (KDG, KAG, equally KDG and KAG) varied among the Think Tank roadmaps. Roadmaps that mostly contained knowledge development gaps were *Soil sealing and reuse urban soils*, *Soil biodiversity* and *Desertification and land Degradation* (9, 8, and 7 KDGs, respectively, Table 1). By opposition, roadmaps that mostly contained knowledge application gaps were *Soil erosion, Soil literacy* and *Soil organic carbon* (4 KAGs in each, Table 1). Overall, knowledge development gaps always appeared as dominant.

Each Think Tank roadmap also provided the relevance of the knowledge gaps for the different sectors that cover the four main land use types as distinguished by the Soil Mission Document 'A Soil Deal for Europe' (Table 2). Thirteen knowledge gaps have not (yet) been classified: ten from the *Soil biodiversity* roadmap and three from the *Soil organic carbon* roadmap. Interestingly, the majority of all identified knowledge gaps were relevant for all sectors, except for the *Soil organic carbon* and *Soil sealing and reuse urban soils* roadmaps, that were primarily relevant for the agricultural and urban-industrial sectors, respectively (Table 2).

Table 2. The number of prioritized knowledge gaps that are relevant for the four sectors of the Soil Mission: Agriculture, Forestry, Urban-Industrial, and Nature. NA means that this Think Tank did identify the relevant sector for the knowledge gaps

Think tank roadmap	Agriculture	Forestry	Urban and Industrial	Nature
EU global footprint on soils	4	4	4	4
Desertification and land degradation	9	9	9	8
Soil biodiversity	NA	NA	NA	NA
Soil erosion	10	10	10	10
Soil literacy	10	10	10	10
Soil organic carbon	5	1	0	1
Soil pollution	10	8	8	8
Soil sealing and reuse urban soils	0	0	10	0
Soil structure	11	12	8	9
Total	**55**	**50**	**55**	**46**

2.2 Specification and number of actions and bottlenecks

In total, Think Tanks identified 235 actions to solve the identified 86 prioritized knowledge gaps (Table 3).

At the time of developing the Think Tank roadmaps, SOLO distinguished two types of actions:

- **Research: '**Research and experimental development (R&D) comprises the creative and systematic work undertaken in order to increase the stock of knowledge - including knowledge of humankind, culture and society' (Glossary European Union, 2025).
- **Innovation: '**Innovation is defined as a new or significantly improved product (good or service) that is or might be introduced to the market, or the introduction within an enterprise of a new or significantly improved process' (Glossary European Union, 2025).

The Think Tanks have characterized the majority of the actions as equally Research and Innovation in nature (106 out of 235 actions). The remaining actions were either separately classified as Research (58), Innovation (also 58), or were not (yet) specified (13, Table 3). Most actions that were classified as both Research and Innovation originated from the *Soil organic carbon* and *Soil pollution* roadmaps (86 out of 106 actions). Most Think Tank roadmaps contained a mix of both Research and Innovation actions, except for the *Soil biodiversity* roadmap that mostly identified Research actions and the *Soil literacy* roadmap that mostly identified Innovation actions (Table 3).

Think Tanks identified a total of 304 bottlenecks in their roadmaps, with an average of 33 bottlenecks per Think Tank (Table 3). The *Desertification and* l*and degradation* roadmap stands out with the highest number of bottlenecks (117). This number is the result of a different systematics of this Think Tank compared to the others, as the same bottleneck was applied to multiple actions. When considering the number of unique distinct bottlenecks (27), *Desertification and land degradation* was well in line with the other Think Tanks.

Table 3. The number of actions and bottlenecks to solve prioritized knowledge gaps that Think Tanks have identified in their roadmaps. The actions are further classified into Research actions (R), Innovation actions (I), equally Research and Innovation actions (R and I), or unspecified.

Think Tank roadmap	Total nr. of actions	Research (R)	Innovation (I)	Equally R and I	Unspecified	Bottlenecks
EU global footprint on soils	9	0	0	0	9	15
Desertification and land degradation	15	2	5	8	0	117
Soil biodiversity	33	18	3	11	1	16
Soil erosion	28	15	10	0	3	4
Soil literacy	21	7	14	0	0	27
Soil organic carbon	48	0	0	48	0	39
Soil pollution	40	0	2	38	0	27
Soil sealing and reuse urban soils	41	16	24	1	0	32
Soil structure	0	0	0	0	0	27
Total	**235**	**58**	**58**	**106**	**13**	**304**

2.3 The thematic landscape of required soil research and innovation

Following the SOLO deliverable on 'Typology of Drivers of Soil Health across European Union(D3.1), the knowledge gaps of the Think Tank roadmaps were classified into six categories, in agreement with Chowdhury et al. (2024),:

1) Technology and Management.
2) Nature and Environment.
3) Policy and Institutional Arrangements.
4) Demography.
5) Socio-cultural context.
6) Economy.

These six categories are based on (Mitter et al., 2020; van Vliet et al., 2015). Most knowledge gaps were primarily categorized as Technology and Management, including knowledge gaps on soil monitoring (Table 4). The second most frequently occurring category was the Socio-cultural context, followed by Nature and Environment. The category of Demography was the least frequently occuring category (Table 4). Some knowledge gaps were rather holistic and could therefore encompass multiple categories. The performed categorization for Table 4 was only based on the main focus of the knowledge gaps though, so that all knowledge gaps were only assigned to one, and not multiple, categories. A more in-depth thematic exploration was further conducted, allowing the allocation of knowledge gaps to multiple categories with related narratives for each category. This deeper exploration is explained in the next section.

Table 4. The number of knowledge gaps that Think Tanks have identified in their roadmaps that primarily belong to each of the six main categories.

Knowledge gap categories	Nr. of knowledge gaps that primarily belong to respective category
Technology and Management	28
Nature and Environment	16
Policy and Institutional Arrangement	4
Demography	2
Socio-cultural context	23
Economy	5

3 Synergies and trade-offs across Mission Objectives

This section presents the “horizontal integration” of the Think Tank outputs. The final results of this integration are 1) Strategies for effectively addressing the synergies and trade-offs when developing actions to solve knowledge gaps across different Mission Objectives by overcoming potential overlaps; and 2) Strategies to overcome implementation bottlenecks;

3.1 Methodology on finding synergies and trade-offs

This section 3.1 first provides a short summary of the overall approach that was used for finding synergies and trade-offs across regions (3.1.1). Then, the different methodological steps in the approach are explained in more detail in the next subsections (3.1.2)

3.1.1 Summary methodology

Optimization of resource allocation to solving knowledge gaps requires the identification of synergies and trade-offs among Mission Objectives. Resources that allow executing research and innovation actions can only be spent once. Synergies therefore occur when a single research or innovation action may help to solve multiple knowledge gaps across various Mission Objectives (Figure 3). Trade-offs then arise when addressing one knowledge gap limits the ability to address a knowledge gap of another Mission Objective, so that selecting one research or innovation action comes at the expense of others (Figure 3). In order to determine synergies and trade-offs, we analysed the distribution of knowledge gaps among Mission Objectives and identified whether the gaps were allocated within (i.e., a synergy) or outside (i.e., a trade-off) the common-ground (Figure 3).

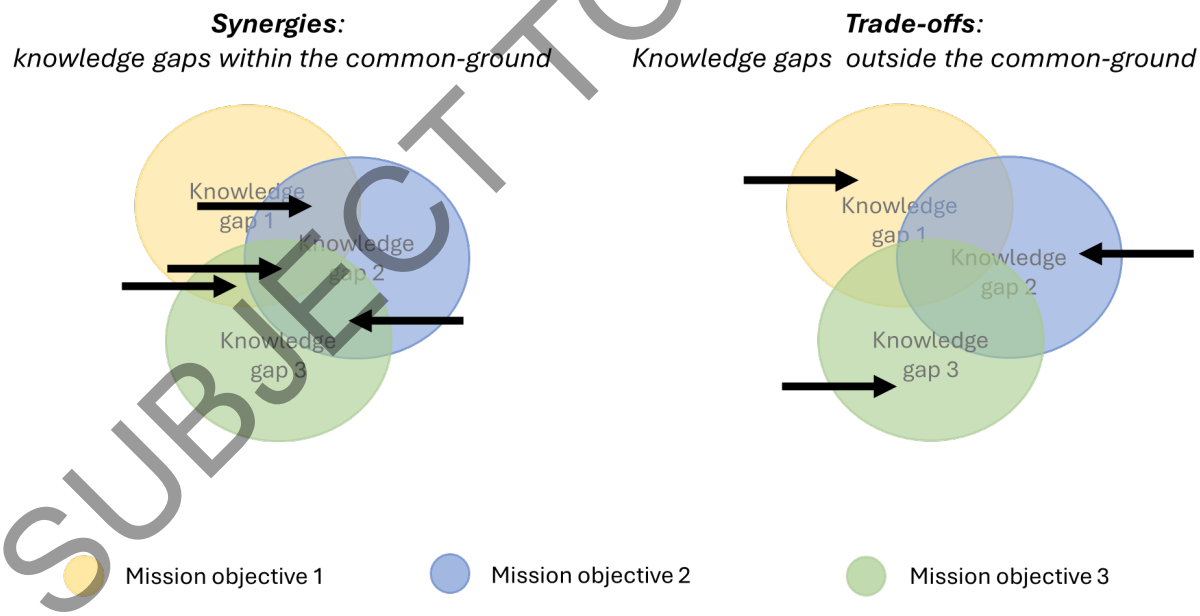

Figure 3. Synergies occur when knowledge gaps overlap among Mission Objectives to such extent that they can be solved simultaneously by the same research or innovation activity. Trade-offs occur when solving different knowledge gaps among Mission Objectives requires separate and independent actions, so that selecting one research or innovation action comes at the expense of others. Figure updated from Periodic Report 1, 2024.

We developed an objective and quantitative approach to horizontally integrate the Think Tank roadmaps, by combining bottom-up and iterative co-construction approaches with a 'thematic synthesis' approach based on (Barnett-Page and Thomas, 2009). A thematic synthesis was performed by translating recurring concepts found in the knowledge gap descriptions of the Think Tank roadmaps into overarching knowledge gaps that apply to multiple (preferably all) Mission Objectives. Two examples are:

1. One Think Tank roadmap can have a knowledge gap described as 'There is a lack of a standardized method to monitor…'. Another Think Tank roadmap could state 'We need harmonized indicators and benchmarks to analyse annual trends in…". Both knowledge gap descriptions refer to the need for a standardized monitoring scheme with clear reference values. The different wording used in this first example can be translated to an overarching knowledge gap, named 'standardized monitoring.'
2. The overarching main theme also covers subthemes. For example, some knowledge gaps pinpoint the 'standardization of soil health indicators', whereas others evolve as 'setting benchmarks'. Subthemes in this second example could therefore be 'standardization', and 'benchmarks'.'

Executing a thematic synthesis usually involves the following steps (Gough et al., 2012):

1) Finding and extracting relevant study material.
2) Evaluating and (if necessary) improving the quality of study material.
3) Formulating descriptive overarching themes, in SOLO the so-called 'subthemes.'
4) Clustering the subthemes to further develop conceptual analytical themes (in SOLO: 'main overarching themes') from the subthemes.

WP4's team led steps 1 and 2 in close collaboration with WP 1 and WP2 (including all Think Tank leaders). We extracted, complemented, and improved the consistency of the structure and formulation of the Think Tank roadmaps. Each Think Tank roadmap was then presented as an Outlook chapter in the Outlook on Soil Health 2025, that contains and introduction and state-of-the art of the Mission Objective, and elaborate descriptions of the top ten most important knowledge gaps. Each Outlook chapter further contains a roadmap in table format in the Supplementary Information, that provides short descriptions and characterizations of knowledge gaps, bottlenecks and actions, and displays their relationships. The roadmap tables became the basis for finding the synergies and trade-offs across Mission Objectives (Figure 4).

* These think tanks covers the original mission objective 'Improve soil structure to enhance soil biodiversity'

Figure 4. Summary of the workflow to find synergies and trade-offs across Soil Mission Objectives by finding the overarching knowledge gaps (KGs) and bottlenecks (BNs) and relating them to each other. Basis for this synthesis was provided by the Think Tank roadmaps linked to the Soil Mission Objectives.

After completing steps 1-2 of the thematic synthesis, WP4 used online meetings and the SOLO project meeting in Lund (Spring 2025) to iteratively execute steps 3 and 4 in collaboration with WP2 (including TT leaders). This iterative process resulted in nine overarching main knowledge gaps and six overarching bottlenecks. WP4 assigned each of the 86 knowledge gaps and 304 bottlenecks of the Think Tank roadmaps to one or more of the overarching main and subthemes (Figure 4). This allocation was checked and revised by all Think Tank leaders. Eventually, we related the overarching bottlenecks to the overarching knowledge gaps in collaboration with WP3 to find the leverage points in overcoming implementation bottlenecks (Figure 4). This analysis helped to determine which bottlenecks hinder solving a wide range of knowledge gaps, and which bottlenecks hinder solving only a few or very specific knowledge gaps. Overcoming bottlenecks that are related to a wide range of knowledge gap from leverage points to obtain the required knowledge to achieve the different Mission Objectives. The different steps for the thematic are further developed and explained in more detail in the next section 3.1.2.

3.1.2 Thematic synthesis in SOLO

1. Find and extract relevant study material

Table roadmaps were used as basic study material for the thematic synthesis. Each table roadmap summarizes and characterizes the top ten prioritized knowledge gaps with their associated bottlenecks and actions, and discerns their interactions (Table 5):

Table 5. Categorization of the table roadmaps developed by the Think Tanks

Knowledge gap	**Bottleneck**	**Action**
Title	Description	Description
Description	Relation to knowledge gaps and/or action	Type: research or innovation
Relevance for sector		Timeframe
Type: knowledge development or application gap		Relation to knowledge gaps and/or bottleneck
Priority to be solved: High, Middle, Low		

The more elaborate explanations of the knowledge gaps in the Outlook chapters were also taken into account when developing the overarching themes, to ensure that the knowledge gaps were fully understood, and to complement the information used for the thematic synthesis if relevant.

2. Evaluate and (if necessary) improve quality of the study material

Putting all thematic table roadmaps together into one spreadsheet revealed a highly diverse structure of the individual Think Tank roadmaps. In some cases, an adequate representation of the Mission Objectives required the structure of the roadmap to deviate from the proposed one. In other cases, the consistency across roadmaps could be improved by clarifying the roadmap structure, reformulating the different roadmap elements, or by complementing missing information. For the cased that the consistency of the table roadmaps could be further improved, the following actions were taken:

1) WP4 generated instructions how to complement missing information in the table roadmaps in a consistent manner.
2) A core writing team (WP4, WP2, WP1) provided suggestions to reformulate knowledge gaps and bottlenecks in a more consistent manner. For instance, each bottleneck was rephrased as “X hinders/causes Y”, and all bottlenecks related to European research funding were removed.

Think Tanks implemented the new instructions, resulting in completer and more consistent table roadmaps that provided the basis of this deliverable and allowed a deeper thematic analysis. Further inconsistencies were solved during a subsequent project meeting in Évora, that will lead to an improved roadmap structure to be implemented in 2026, to deliver the final overarching roadmap (D4.3).

3. Finding overarching knowledge gaps: formulating and clustering main and subthemes

An iterative process was used to identify and cluster the descriptive subthemes into overarching main themes, leading to the overarching knowledge gaps (Figure 5).

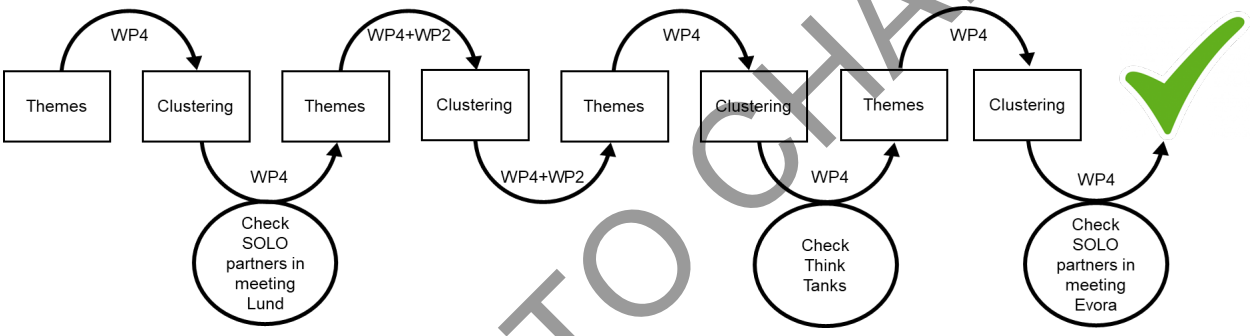

Figure 5. Overarching knowledge gaps were identified using an iterative process of defining descriptive subthemes that were clustered into more overarching main themes, with regular inputs from various SOLO partners from WP4, WP2 and the participants of the plenary SOLO project meetings. The definitions of the overarching knowledge gaps were revised upon input from all Think Tanks, as well as the allocation of their knowledge gaps into these themes.

WP4 first formulated keywords that represented the descriptive themes of the original knowledge gaps, and clustered them into overarching main themes (i.e., ‘conceptual analytical themes’) after internal discussions, using Excel and Miroboard. WP4 represented these results to all SOLO partners during the project meeting in Lund, resulting in the foundation of the core writing team (see previous section), as well as in a change of software and changes in the formulation of the overarching themes. Once all Think Tanks had incorporated the feedback of the core writing team, WP4 reformulated the descriptive subthemes and updated their clustering in overarching main themes, with inputs from WP2. Subsequently, the knowledge gaps of each roadmap were allocated to one, or multiple, overarching sub- and main knowledge gaps via line-to-line coding of the summarized knowledge gap descriptions with the text analysis program NVIVO 15. The improved structured allocation of knowledge gaps into overarching themes resulted in new insights regarding the formulation and clustering of overarching knowledge gaps, which were implemented by WP4. Subthemes were removed if their assigned knowledge gaps all belonged to the same Think Tank. In total, this synthesis resulted in nine main overarching knowledge gaps to which the 86 individual knowledge gaps of the Think Tank roadmaps were assigned. Then, the allocation of the individual knowledge gaps into the main overarching knowledge gaps was sent out to all Think Tanks, in combination with the definition of the main overarching knowledge gaps

to enhance the quality of feedback from the Think Tanks. WP4 incorporated the feedback of all Think Tanks and discussed the results in the Évora project meeting, finalizing the thematic synthesis of the knowledge gaps.

4. Finding overarching bottlenecks: formulating and clustering main and subthemes

Overarching bottlenecks were synthesized from the reformulated bottlenecks (see 4.1.2) in a similar fashion as for the overarching knowledge gaps, in a more simplified procedure (Figure 6).

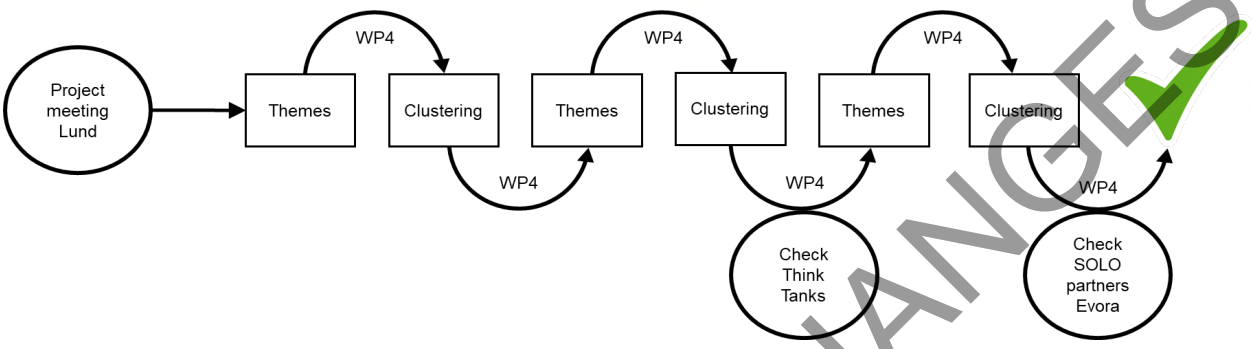

Figure 6. Overarching bottlenecks were identified using an iterative process of defining descriptive subthemes that were clustered into more overarching main themes, with regular inputs from various SOLO partners. The definitions of these main overarching bottlenecks were revised upon input from all Think Tanks, as well as the allocation of their bottlenecks into the main themes.

The format of the reformulated bottlenecks was “X hinders Y”. Part ‘X’ represents the core of the problem that prevents taking the required action(s) to solve respective knowledge gap, while part ‘Y’ represents the consequence of that problem. Without the link to a clear action, part ‘Y’ cannot be clearly delineated. The thematic synthesis therefore only focused on the core of the problem (part ‘X’). WP4 iteratively identified descriptive themes from the original bottlenecks and clustered them into overarching main themes (i.e., ‘conceptual analytical themes’) in Miroboard and NVIVO 15. The resulting six main overarching bottlenecks covered 297 out of 304 individual bottlenecks. Ssven bottlenecks did not belong to any of the overarching themes and were left out of the subsequent analyses. These seven bottlenecks originated from 3 Think Tank roadmaps (1 from *EU global footprint,* 4 from *Soil organic carbon* and 2 from *Soil structure)*. After two internal revision rounds in WP4, the allocation of the individual bottlenecks into the main overarching bottlenecks was sent out to all Think Tanks, as well as the definitions of the main bottlenecks. The feedback was incorporated, presented, and discussed during the Évora project meeting, thus finalizing the thematic synthesis of the bottlenecks.

Relating overarching bottlenecks to knowledge gaps

Each individual knowledge gap was related to one or more specific bottlenecks in the Think Tank roadmaps. All knowledge gaps and all but seven bottlenecks could be allocated to one or several of the overarching knowledge gaps and bottlenecks. Using the original relationships between the specific knowledge gaps and bottlenecks in the Think Tank roadmaps, the relationships between the overarching main knowledge gaps and bottlenecks was identified (Figure 7). These relationships unveiled the leverage points in overcoming implementation bottlenecks, since

addressing certain bottlenecks can solve a broad spectrum of knowledge gaps, while addressing others may not be as relevant.

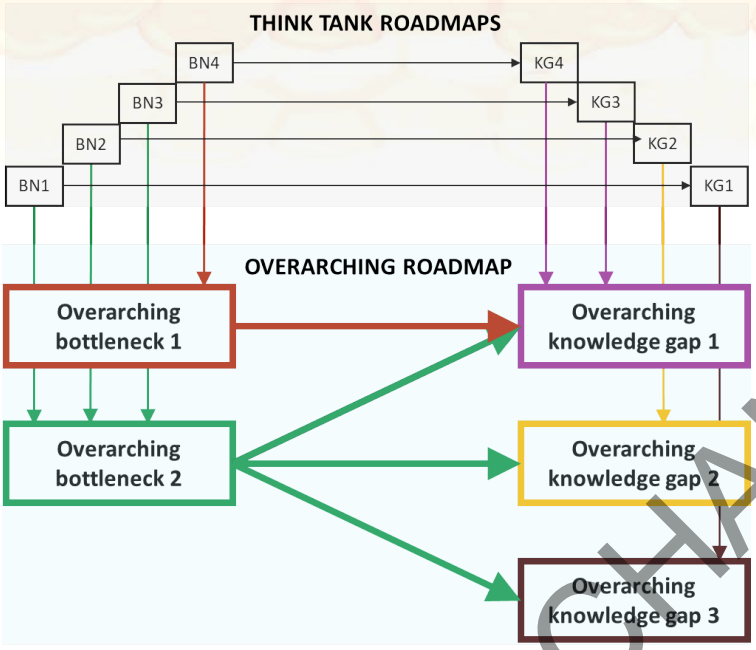

Figure 7. The relationships between the overarching main knowledge gaps and overarching bottlenecks were derived from the relationships between the original specific bottlenecks and knowledge gaps in the Think Tank roadmaps. Overarching bottlenecks that are related to multiple overarching knowledge gaps form the leverage points, as overcoming these bottlenecks will solve multiple types of knowledge gaps. In contrast, overcoming some overarching bottlenecks may only result in solving one or few knowledge gaps.

The relationships between overarching bottlenecks and knowledge gaps were derived from manually transferring the applied coding in NVIVO15 to Excel, ensuring that the relationships between bottlenecks and knowledge gaps was conserved. In total, the eight overarching knowledge gaps and six overarching bottlenecks resulted in 48 combinations, and the frequency of each combination was analysed. Those frequencies were translated into coding for the SankeyMATIC.com open-source website by WP3, to construct a flow diagram. The visuals of the resulting figure were then upgraded in photoshop by WP3.

3.2 Synergies and trade-offs in knowledge gaps

The main overarching knowledge gaps, each based on common ground among a number of knowledge gaps, was earlier presented in Figure 3. Section 3.2.1 delineates the common ground, and section 3.2.2 the resulting synergies and trade-offs in knowledge gaps across Mission Objectives.

3.2.1 Identified main overarching knowledge gaps

The thematic synthesis resulted in eight main overarching knowledge gaps (defined in Table 6):

1) Drivers of soil health.
2) Sustainable land and soil management.
3) Soil monitoring.

4) Policy and land use planning.
5) Livelihood, soil stewardship and communication.
6) Impact of soil health on society.
7) Natural soil processes.
8) Economy.

The 'Drivers of soil health' might overlap with other themes, especially with 'Sustainable land and soil management', 'Policy and land use planning', 'Livelihood, soil stewardship and communication', and 'Economy.' To avoid such overlap, we only assigned knowledge gaps to 'Drivers of soil health' if the focus was on understanding the influence of a particular factor (e.g. 'How does tillage affect soil erosion?') on soil health. If knowledge gaps were focused on understanding the process of that factor itself (e.g. 'how can we improve tillage practices to reduce soil erosion?'), or developing and evaluating novel tools (e.g. 'how can we develop machinery that reduces erosion?"), these gaps were assigned to one of the other overarching knowledge gaps (e.g. 'with 'Sustainable land and soil management'). Finally, we identified a ninth overarching theme 'Research requirements' for being transversal across knowledge gaps. In this theme, information was provided on what *type of approach* is needed to develop the required knowledge, rather than *what* knowledge is lacking (Table 6).

Table 6. Main overarching knowledge gaps across the Mission Objectives as identified from the Think Tank roadmaps, including SOLO definitions.

Main overarching knowledge gap	Definition of the main overarching knowledge gaps
Drivers of soil health	Assessment of the presence, distribution and development of drivers, and their effects on (an aspect of) soil health status. This effect can be directly (e.g. environmental factors influencing soil biodiversity) or indirectly (e.g. societal drivers influencing human behaviour changing soil management (which is named 'pressure') that affects soil biodiversity (named 'status'), and even more indirectly (societal drivers for changing soil education that affects soil literacy that affects soil management that affects soil biodiversity). The considered drivers are broad and link to several other overarching knowledge gaps (e.g. lifestyle and soil stewardship, policy and planning). A knowledge gap is only assigned to this overarching knowledge gap 'drivers soil health' if the focus is on understanding the influence of a factor (e.g. 'soil stewardship') on soil health. In all other situations (e.g. understanding the process itself, or developing and evaluating tools and innovations in e.g. communication, economy, soil/land management)) the knowledge gaps are part of the other overarching knowledge gaps and not allocated to the 'drivers soil health' gap.
Sustainable land and soil management	Development, evaluation and implementation strategies of soil and land management practices or systems to restore, conserve, protect, remediate and enhance (an aspect of) soil health, or its resilience, and prevent soil degradation. This theme also includes decision making processes and implementation frameworks related to soil and land management, which influence how soil and land management practices are executed, upscaled and widely implemented.

Soil monitoring	Development and evaluation of frameworks, indicators, methods and benchmarks/baselines for monitoring and evaluating (an aspect of) soil health and soil threats.
Policy and land use planning	Development and/or evaluation of novel policy instruments (e.g. legislation or economic instruments), institutional arrangements, and governance structures that protect and prevent soil degradation and/or enhance (an aspect of) soil health. This theme also includes knowledge gaps about land planning that influence a.o. the land use, as land planning decisions are made at governmental level and are reinforced by institutions.
Livelihood, soil stewardship and communication	Development of understanding on soil stewardship as important factor for soil health. The idea of "stewardship" involves the conscientious and responsible management of resources (in this case soil health) entrusted to one's care, and is greatly influenced by soil literacy. This theme closely relates to 'Sustainable land use and soil management', but focuses more on the human behaviour as a factor driving land and soil management, rather than on specific management and land use practices. This theme also entails the development and evaluation of efficient and/or effective communication and education activities that influence soil stewardship and consequently, human behaviour. Knowledge gaps about lifestyle behaviour and livelihood that influences soil health by e.g. consumption patterns are part of this theme as well.
Impact of soil health on society	Development of understanding how soil health status directly or indirectly impact society, via effects on soil-based ecosystem services, human health and on the socio-economic context of individuals, organizations, countries or society as a whole. Where the other overarching knowledge gap themes relate directly or indirectly to how humans affect soil health, this knowledge gap focuses on how soil health affects humans.
Natural soil processes	Development of understanding of individual and interactive biological, chemical, physical processes in soil. Understanding soil processes is also key to other themes, in particular to understanding soil health drivers and developing sustainable land use and soil management. A knowledge gap is assigned to this theme of 'soil processes' only if the knowledge gap focuses on the soil process(es), without connecting to a broader context like changed soil management or the effect of soil health drivers.
Economy	Development and evaluation of knowledge and innovations within or beyond the way how a country or region produces, distributes, and consumes goods and services, that affect (an aspect of) soil health. Knowledge gaps are included if concerning valuation of ecosystem services and societal/environmental costs, effects of supply chain organization, as well as knowledge gaps concerning market analysis, budget allocation, market needs, or the development of tools that help farmers understand the market.
Research requirements	This theme does not represent a knowledge gap, but instead represents which tools (e.g. maps, models, observations), research types (e.g. inter/transdisciplinary) and specifics about the spatio-temporal approach are specifically mentioned to address identified knowledge gaps.

Most knowledge gaps in the roadmaps were assigned to multiple overarching knowledge gaps. For example, the *EU global footprint on soils* roadmap consisted of only four specific knowledge gaps (Table 1), but has in total fifteen references to the main overarching knowledge gaps (Figure 8.). The most encompassing Mission Objectives, i.e., D*esertification and land degradation* and *Soil pollution,* cumulated the highest number of references linked to the main overarching knowledge gaps, i.e., 48 and 47 respectively (Figure 8.).

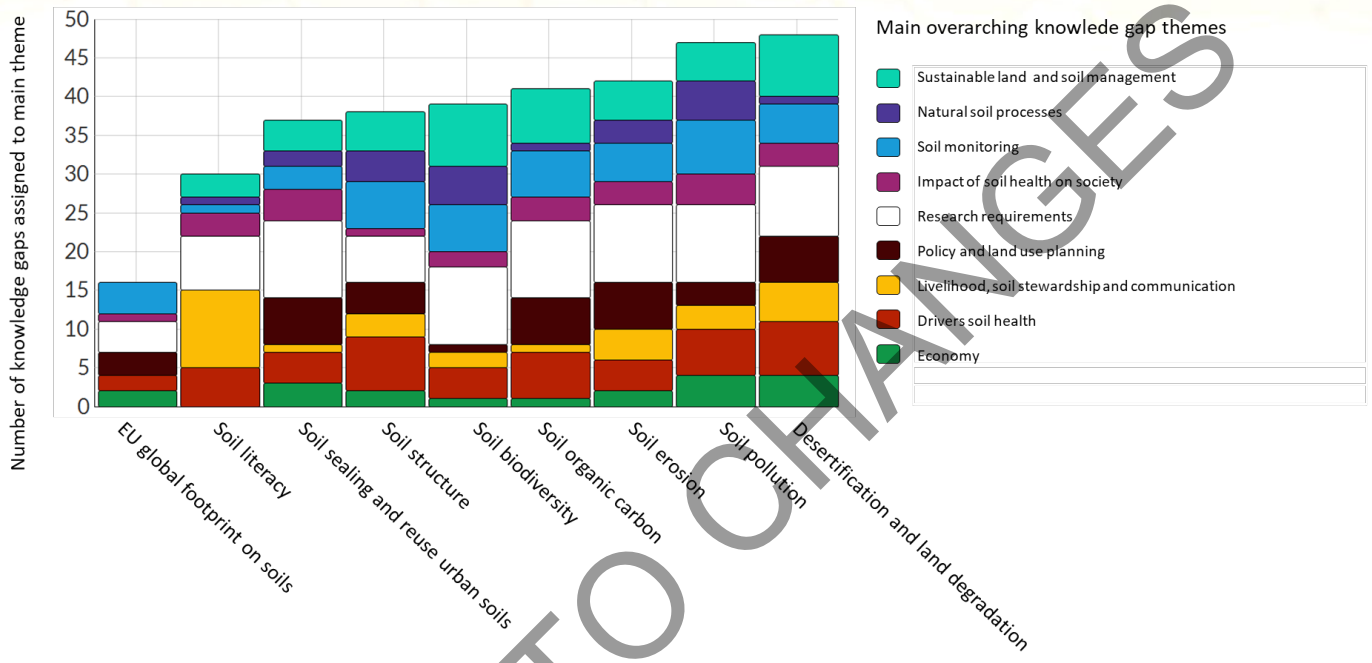

Figure 8. The number of knowledge gaps in each Think Tank roadmap (x-axis) assigned to the main overarching knowledge gap themes (y-axis, the different colours representing the different overarching themes). Since the individual knowledge gaps of each Think Tank roadmap can be assigned to multiple overarching themes, the total number of references to overarching themes is larger than the total number of prioritized knowledge gaps per Think Tank roadmap (Table 1).

3.2.2 Identified synergies and trade-offs in knowledge gaps across Mission Objectives

Synergies

Four synergies could be identified from the common-ground of the overarching knowledge gaps:

1) *All* Think Tank roadmaps had two or more knowledge gaps assigned to 'Drivers of Soil health' (Table 7), which constitute forty percent or more of all knowledge gaps identified by Think tanks (Table 8).
2) Half of the knowledge gaps were somehow related to 'Soil monitoring'. 'Policy and land use planning' was also relevant for most Mission Objectives, except for *Soil literacy* and *Soil biodiversity* (Table 8). Since soil monitoring frameworks are often embedded in policy, many knowledge gaps hence appear to be -often secondarily- related to policy (Table 4).

3) Knowledge gaps about 'Impact of soil health on society' were mentioned in all Think Tank roadmaps, but never appeared as dominant in the Think Tank roadmaps (maximum number of knowledge gaps assigned ≤ 40%,Table 8).
4) All Think Tank roadmaps except *EU global footprint on soils* addressed knowledge gaps related to land and soil management, with 30-80% of the knowledge gaps predominantly focusing on this theme (Table 8). Since the Think Tank roadmap *EU global footprint on soils* focuses on the health of soil outside Europe, improving strategies and decision-making processes of soil and land management practices or systems seems key for soils located within Europe.

For all Mission Objectives, it also appeared that it does not only matter *what* knowledge is developed or applied, but also *how* this is developed or applied: On average 90% of the knowledge gap descriptions contained information on the requirements for solving the specified knowledge gaps (Table 8).

Table 7. The number of individual knowledge gaps of each Think Tank roadmap, and their totals, assigned to each overarching knowledge gap (in columns).

Think Tank roadmaps	Overarching knowledge gaps								
	Drivers soil health	Sustainable land and soil management	Soil monitoring	Policy and land use planning	Livelihood, soil stewardship and communication	Impact of soil health on society	Natural soil processes	Economy	Research requirements
EU global footprint on soils	2	0	4	3	0	1	0	2	4
Desertification and land degradation	7	8	5	6	5	3	1	4	9
Soil biodiversity	4	8	6	1	2	2	5	1	10
Soil erosion	4	5	5	6	4	3	3	2	10
Soil literacy	5	3	1	0	10	3	1	0	7
Soil organic carbon	6	7	6	6	1	3	1	1	10
Soil pollution	6	5	7	3	3	4	5	4	10
Soil sealing and reuse urban soils	4	4	3	6	1	4	2	3	10
Soil structure	7	5	6	4	3	1	4	2	6
Total think tanks	**45**	**45**	**43**	**35**	**29**	**24**	**22**	**19**	**76**

Table 8. Percentage of individual knowledge gaps of each Think Tank roadmap assigned to each overarching knowledge gap (in columns), relative to the total number of knowledge gaps present in the Think Tank roadmap (Table 1). The lowest row presents the average percentage of individual knowledge gaps that were assigned to each overarching knowledge gap.

Think Tank roadmaps	Overarching knowledge gaps								
	Drivers soil health (%)	Sustainable land and soil management (%)	Soil monitoring (%)	Policy and land use planning (%)	Livelihood, soil stewardship and communication (%)	Impact of soil health on society (%)	Natural soil processes (%)	Economy (%)	Research requirements (%)
EU global footprint on soils	50	0	100	75	0	25	0	50	100
Desertification and land degradation	70	80	50	60	50	30	10	40	90
Soil biodiversity	40	80	60	10	20	20	50	10	100
Soil erosion	40	50	50	60	40	30	30	20	100
Soil literacy	50	30	10	0	100	30	10	0	70
Soil organic carbon	60	70	60	60	10	30	10	10	100
Soil pollution	60	50	70	30	30	40	50	40	100
Soil sealing and reuse urban soils	40	40	30	60	10	40	20	30	100
Soil structure	58	42	50	33	25	8	33	17	50
Average think tanks	**52**	**49**	**53**	**43**	**32**	**28**	**24**	**24**	**90**

Trade-offs

There was a trade-off between addressing knowledge gaps on *EU global footprint on soils on soils* and *Soil literacy* on the one hand, and meeting the other Mission Objectives on the other. *EU global footprint on soils* most often did not have any knowledge gaps assigned to one of the overarching knowledge gaps, though this may also be related to only having four prioritized knowledge gaps (Table 1). There were only few knowledge gaps in common between *Soil literacy* and most of the other overarching main knowledge gaps (Table 7). The same two Mission Objectives were the only roadmaps that had all knowledge gaps assigned to the same category : *EU global footprint on soils* had 100% of the gaps assigned to 'Soil monitoring', and *Soil literacy* had 100% of the gaps assigned to 'Livelihood, soil stewardship and communication' (Table 8). In contrast, *Soil erosion* and *Soil pollution* had two or more knowledge gaps associated to each of the overarching knowledge gaps themes. Therefore, *Soil erosion* and *Soil pollution* have high potential for synergetic research and innovation projects, whereas solving knowledge gaps on *EU global food print on soils* and *Soil literacy* will require allocation of specific fundings.

3.2.3 Narratives of the main overarching knowledge gaps

Hierarchy charts of each overarching main and subthemes were produced to demonstrate the underlying structure of the subthemes (Figure 9 -18). In the charts, dark colors indicate the highest level and the lighter the color, the lower the level of the subtheme in the hierarchy. In the charts, the larger the box size, the larger the number of knowledge gap assigned to respective theme (Figure 9). The number of knowledge gaps from the roadmap assigned to each overarching theme are indicated as references. The following sections describe the narratives of all overarching knowledge gaps based on these charts.

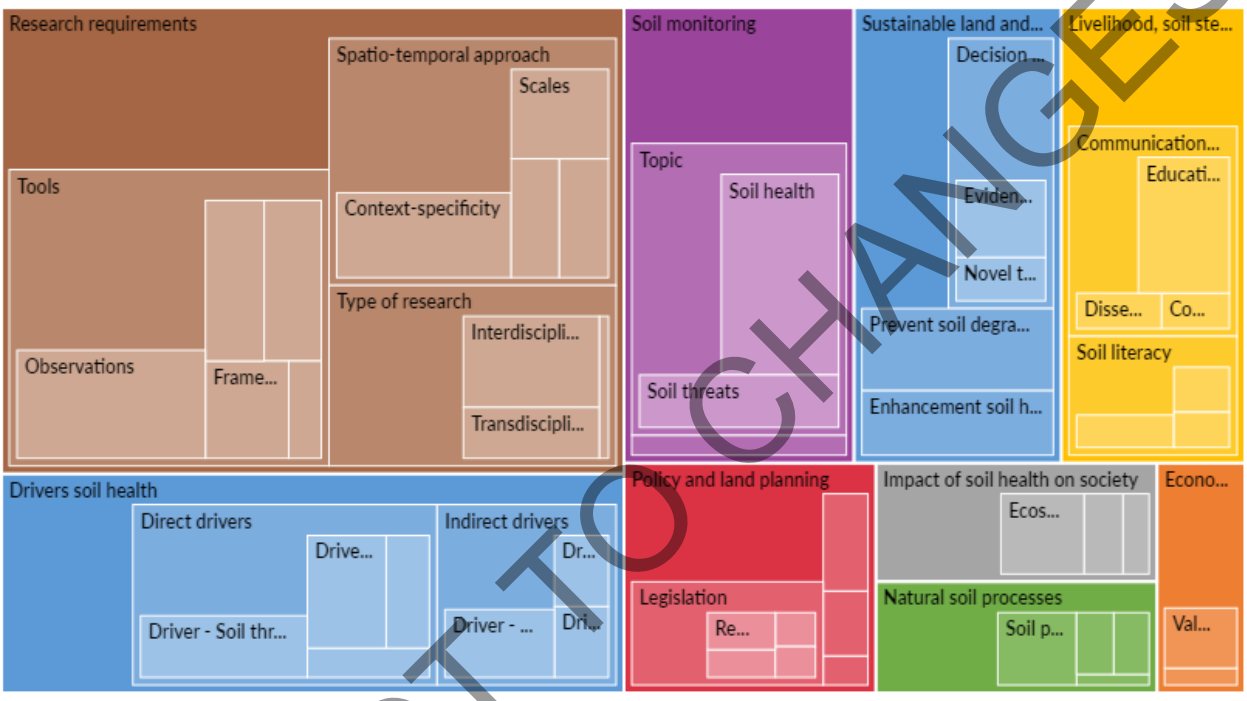

Figure 9. Overall structure of a hierarchy chart: the colours indicate the main overarching knowledge gaps. Box brightness represents the hierarchical level of the subtheme. Box size indicates the number of knowledge gaps that are allocated to each main and subtheme.

Drivers of soil health

Most knowledge gaps were associated to direct drivers of soil health (36 references, Figure 10). Of the specified direct drivers, land and soil management was most important (24 references), followed by factors that threaten soil health (21 references), including both human-induced (e.g. tillage, drainage) and natural (e.g. forest fires) disturbances or threats. Seven knowledge gaps specifically described the need to study the vulnerability of soil to these direct threats. The effect of climate change on soil health (10 references), and the effect of the natural variability of the environment on soil health (13 references) including factors as soil type, pedoclimatic zone, soil properties deriving from pedogenesis, or local environmental and climate conditions, were recurrent across Think Tank roadmaps.

There were 23 knowledge gaps allocated to indirect drivers, of which 21 references referred to the effect of the socio-economic context on soil health, 11 references on the effect of policy and planning, and also 11 references on livelihood and soil stewardship (Figure 10).

Some other drivers were not mentioned frequently enough in the roadmaps to become a subtheme. In such cases, the knowledge gaps were only assigned to the main overarching theme 'Drivers of soil health,' but were not further allocated to a specific subtheme.

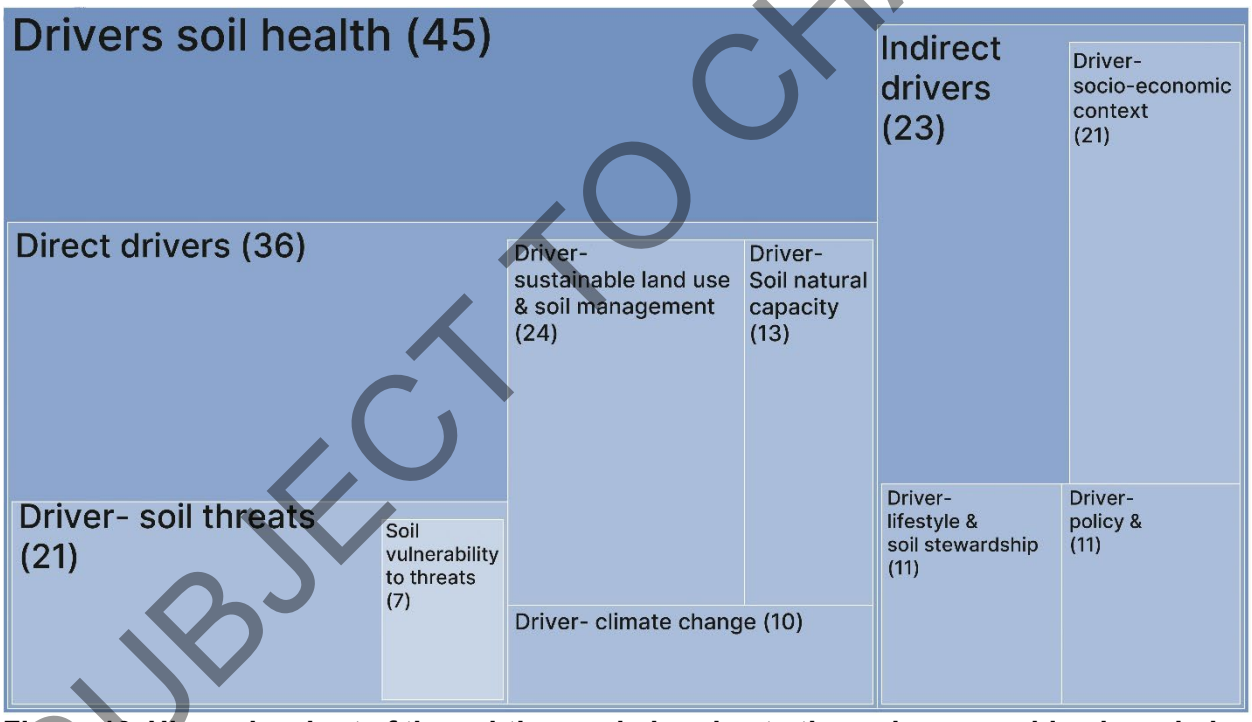

Figure 10. Hierarchy chart of the subthemes belonging to the main overarching knowledge gap theme 'Drivers of soil health.' Box brightness represents the hierarchical level of the subtheme. Box size indicates the number of knowledge gaps that are allocated to each main and subtheme.

Soil monitoring

The vast majority of knowledge gaps that relate to soil monitoring specify what topic needs to be monitored (39 references, Figure 11). Most of the knowledge gaps request a monitoring of soil health per se (29 references), while many others demand the monitoring of the threats leading to soil health degradation (18 references). Within soil health monitoring, most knowledge gaps solicit the development and evaluation of standardized and suitable indicators to measure (an aspect of) soil health and adequate and standardized methods to measure these indicators (17 references). Around half of the knowledge gaps also seek developing and evaluating benchmarks for soil health indicators to allow a comparable assessment of soil health (9 references). Likewise, many gaps request the standardization of indicators and methods for a comparable assessment of the severity of soil threats (5 references), and to a lesser extent the development of environmental standards or baselines (2 references). Eight knowledge gaps also explicitly indicate that soil health needs to be monitored on another location than where a certain soil driver or event occurs or has occured (8 references, Figure 11).

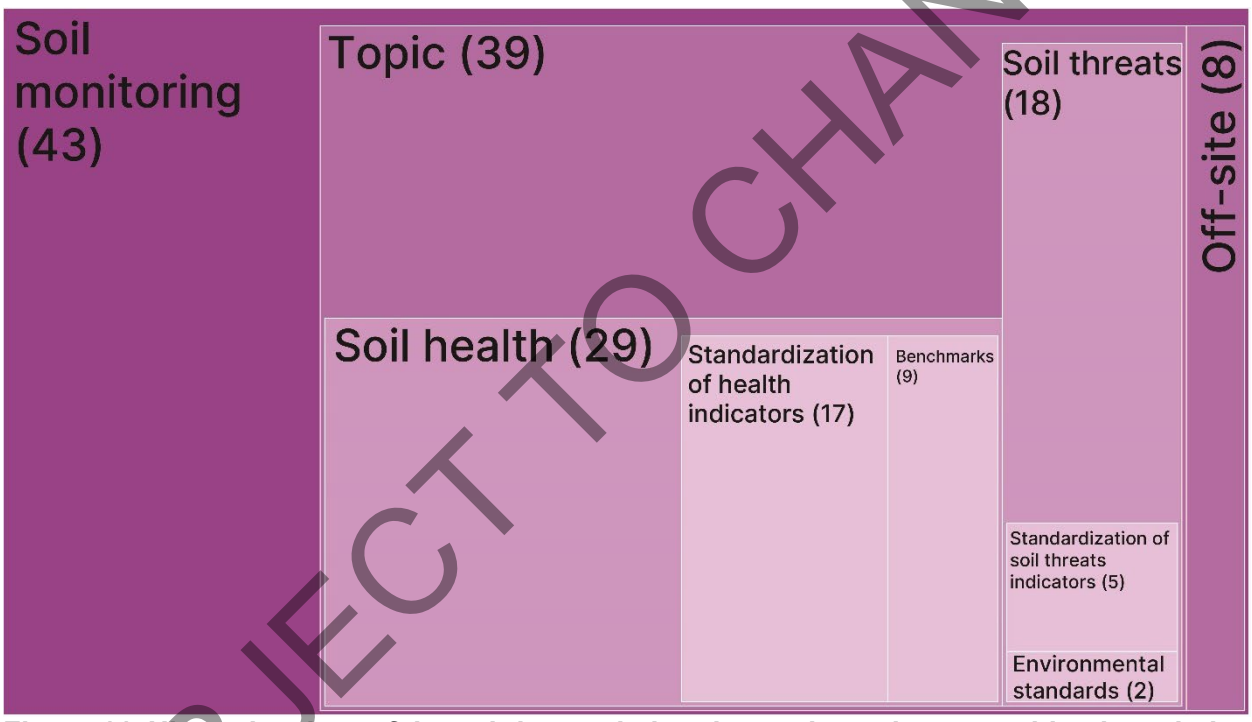

Figure 11. Hierarchy chart of the subthemes belonging to the main overarching knowledge gap theme 'Soil monitoring.' Box brightness represents the hierarchical level of the subtheme. Box size indicates the number of knowledge gaps that are allocated to each main and subtheme.

Impact of soil health on society

The main theme 'Impact of soil health on society' only had one level of three subthemes (Figure 12). Most knowledge gaps were about assessing and evaluating what ecosystem services soils provide to humans (17 references). More indirectly, 8 knowledge gaps described the need to better understand how soil health status impacts the socio-economic context of individuals, organizations, countries, or society as a whole. This subtheme also identifies knowledge gaps about the socio-economic effects in broader society by taking measures that aim to improve soil health status. Finally, the need to understand the direct and indirect effect of soil health status on human health was also a recurring theme (5 references, Figure 12).

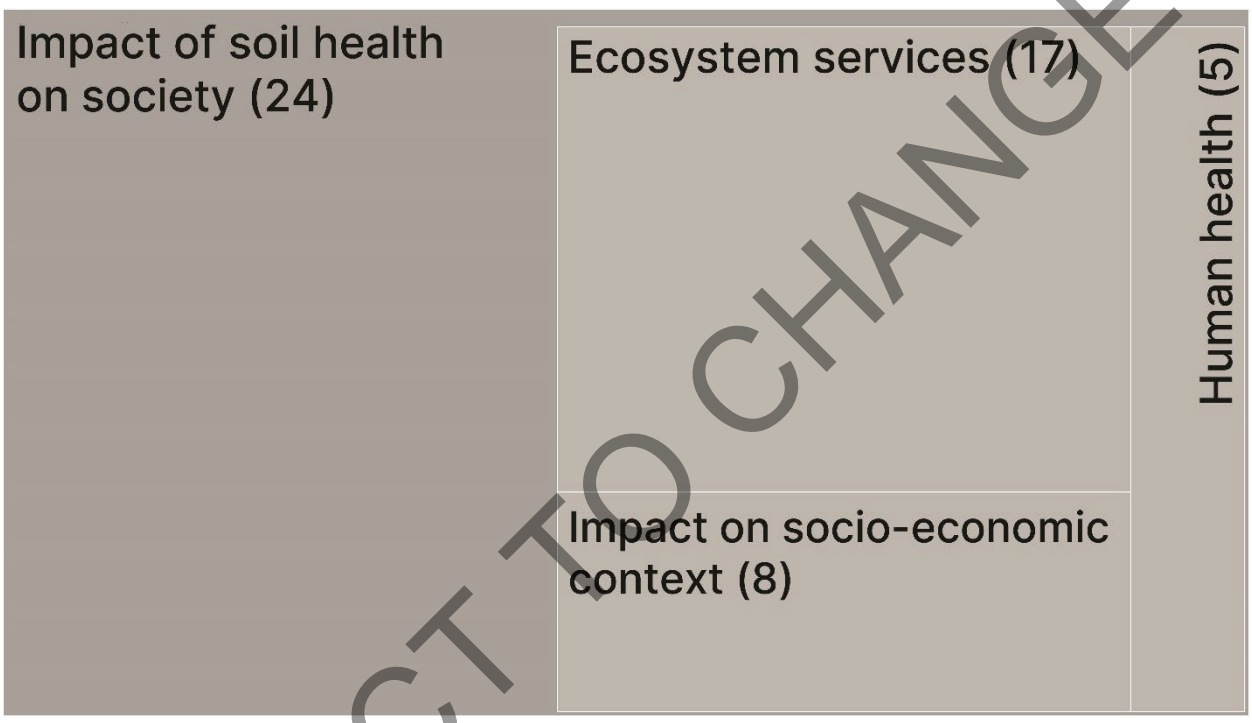

Figure 12. Hierarchy chart of the subthemes belonging to the main overarching knowledge gap theme 'Impact of soil health on society.' Box brightness represents the hierarchical level of the subtheme. Box size indicates the number of knowledge gaps that are allocated to each main and subtheme.

Policy and land planning

Most knowledge gaps belonging to the main theme 'Policy and land planning' specifically address gaps concerning the legislation (16 references) at European (7 references), national (5 references) and regional (4 references) scale), especially regarding the harmonization of legislation and the definitions used in regulatory frameworks (9 references, Figure 13). Developing land planning processes that influence soil health was another recurring theme gathering several knowledge gaps, such as reducing the granting building permits leading to soil sealing (9 references). Other recurring knowledge needs included developing novel governance mechanisms that protect and/or stimulate to increase (an aspect of) soil health (6 references), and improving the economic instruments that support the implementation of policy such as subsidies and taxes (3 references, Figure 13).

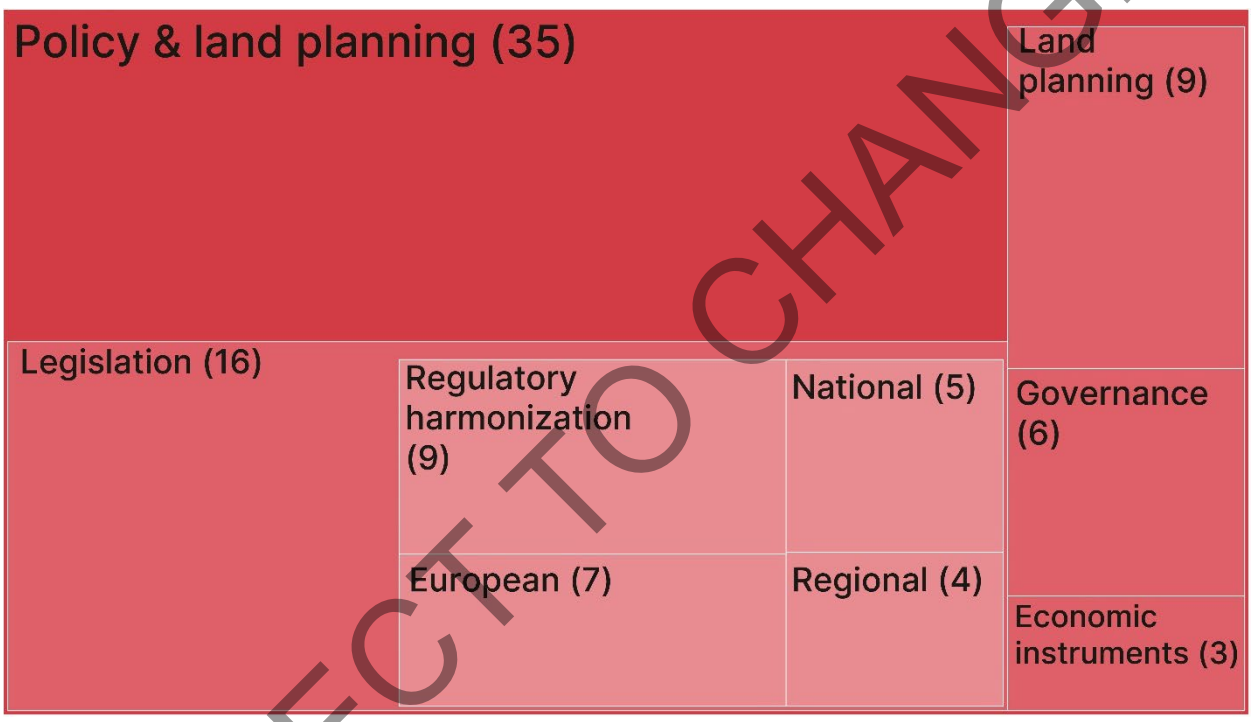

Figure 13. Hierarchy chart of the subthemes belonging to the main overarching knowledge gap theme 'Policy and land planning.' Box brightness represents the hierarchical level of the subtheme. Box size indicates the number of knowledge gaps that are allocated to each main and subtheme.

Livelihood, soil stewardship and communication

This theme consists of two different but complementary pillars. The first one includes knowledge gaps adressing the drivers of soil literacy influencing how humans directly (e.g. land managers) and indirectly (e.g. consumer and political choices) take care of soils, central to soil stewardship. The second pillar includes knowledge gaps about developing effective and efficient communication activities that aim to improve soil literacy and consequently, soil stewardship. Most knowledge gaps focus on this second pillar (22 references), especially via education (13 references), and to a lesser extent dissemination (8 references) and communication activities (6 references, Figure 14). Within education, there is an similar focus on developing novel pedagogical strategies (9 references) and developing novel didactic content about soils (8 references). Developing and improving citizen science as educational tools is also suggested for multiple Mission Objectives (3 references). When it comes to understanding soil literacy, most of the knowledge gaps identified (10 references) specifically mention understanding and altering the attitude of people related to their feelings, values and moral agency (concern for soil, or soil stewardship) towards soils (definition soil stewardship from: Outlook on the knowledge gaps related to soil literacy, 2025). A comparable number of gaps (8 references) specifically mentions understanding and altering the competencies of people, entailing the human abilities, capabilities and knowledge that directly (e.g. soil management) and indirectly (e.g. consumers' choices) influence soil health (definition soil stewardship from: Outlook on the knowledge gaps related to soil literacy, 2025). A relevant number of other gaps also mentions understanding and directly altering human behaviour (6 references, Figure 14).

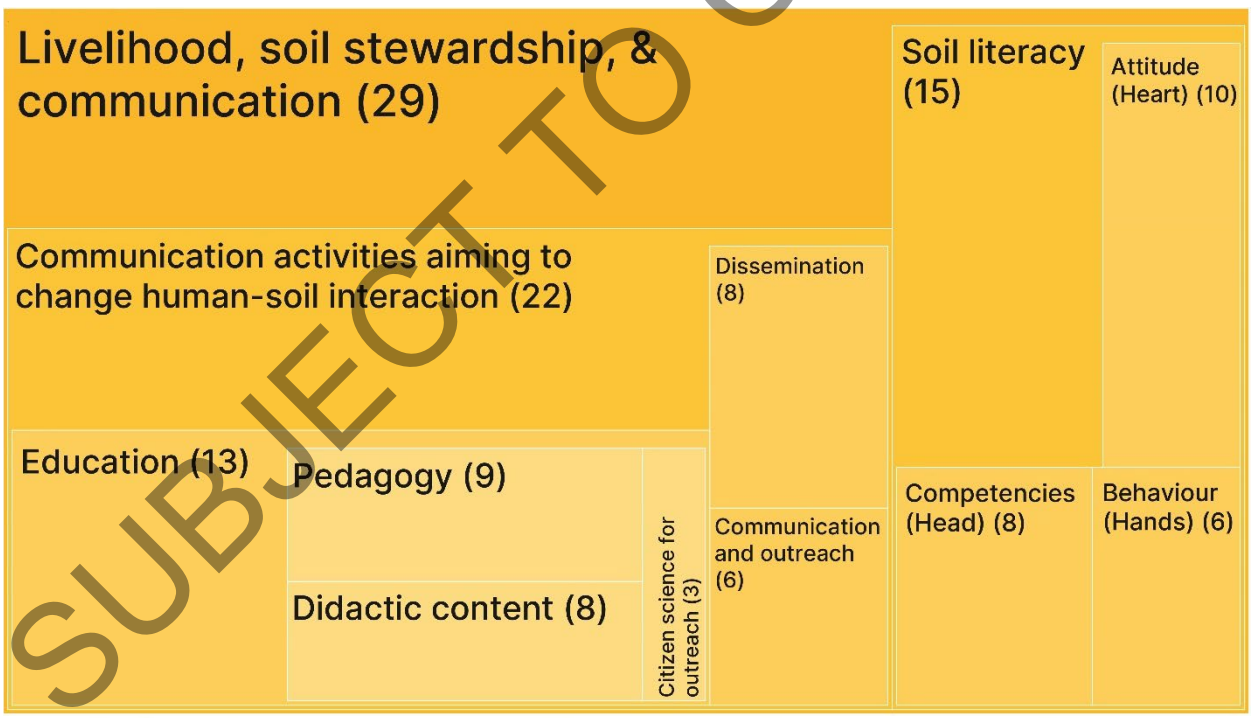

Figure 14. Hierarchy chart of the subthemes belonging to the main overarching knowledge gap theme 'Livelihood, soil stewardship and communication.' Box brightness represents the hierarchical level of the subtheme. Box size indicates the number of knowledge gaps that are allocated to each main and subtheme.

Natural soil processes

The main overarching theme of 'Natural soil processes' shows only one level of four subthemes (Figure 15). The majority of the knowledge gaps addressed the need to better understand the processes that underly soil functioning and, consequently, soil-based ecosystem services (15 references, Figure 15). Less frequently mentioned overarching knowledge gaps described the need to better understand the transport, behaviour and fate of soil compounds such as soil particles, nutrients, organic matter and soil pollutants (6 references), and to better characterize soil biota, including questions related to taxonomy and the identification of keystone species (6 references). Finally, the need to better understand biotic and abiotic interactions with soil organic matter that are relevant for e.g. carbon persistence was mentioned by two different Think Tanks (Figure 15). Identified knowledge gaps covered more natural soil processes besides those that were specified in the different subthemes, but they did not occur often enough to become a subtheme and were therefore only assigned to the main overarching theme 'Natural soil processes.'

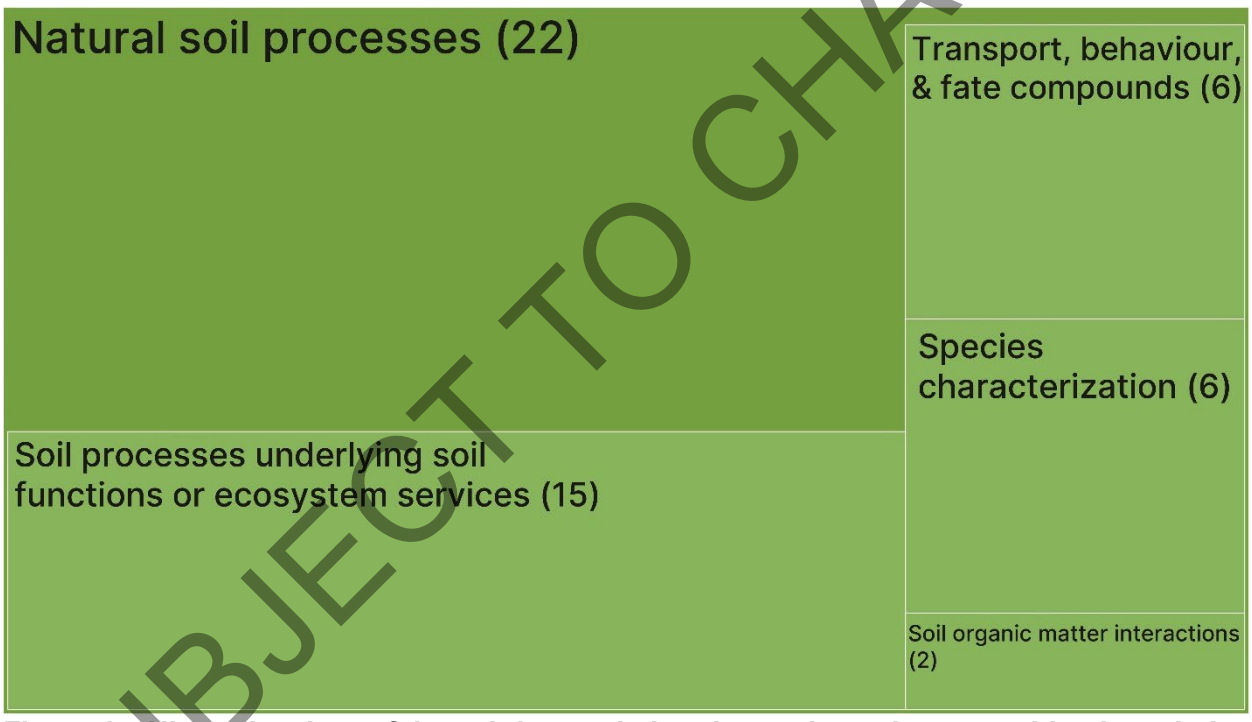

Figure 15. Hierarchy chart of the subthemes belonging to the main overarching knowledge gap theme 'Natural soil processes.' Box brightness represents the hierarchical level of the subtheme. Box size indicates the number of knowledge gaps that are allocated to each main and subtheme.

Sustainable land and soil management

Most knowledge gaps requesting the development of strategies or practices to improve the sustainability of land and soil management especially focused on preventing soil degradation (30 references), and improving the current soil health status (24 references) by restoration or remediation (Figure 16). Improving decision-making in land and soil management is also needed to both prevent soil degradation and improve soil health, so that this topic was also often present in the knowledge gap description (26 references). In particular, the need to develop more evidence-based decision-making processes in land and soil management was often mentioned (18 references), as well as developing decision tools to support soil and land managers in decision-making (10 references, Figure 16).

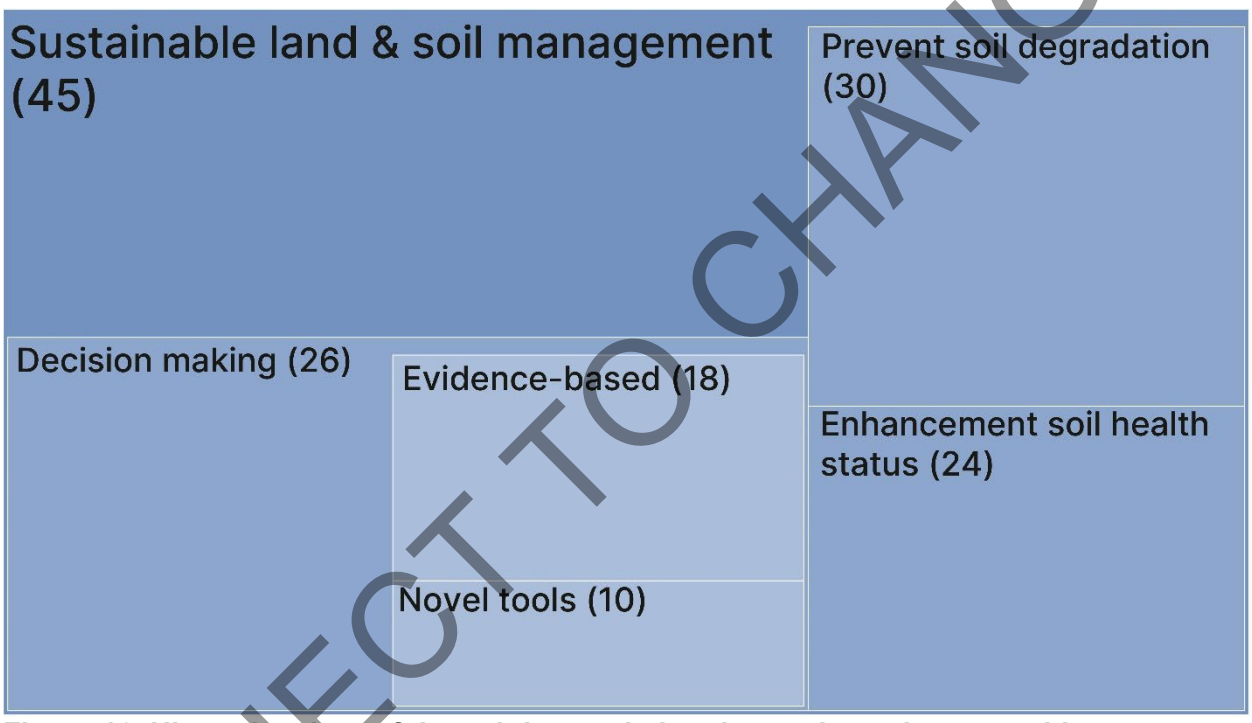

Figure 16. Hierarchy chart of the subthemes belonging to the main overarching knowledge gap theme 'Land and soil management.' Box brightness represents the hierarchical level of the subtheme. Box size indicates the number of knowledge gaps that are allocated to each main and subtheme.

Economy

The overarching main theme 'Economy' turned out to be the simplest one, with only two subthemes (Figure 17). Most knowledge gaps mention the need to develop and evaluate strategies to economically value (an aspect of) soil health, e.g. by financially rewarding soil-based ecosystem or 'true pricing', a concept that includes societal or environmental (including soil) costs in the market price (10 references). Another recurring theme was to develop novel structures in the supply chain that favour soil health (3 references, Figure 17). Some knowledge gaps contained other information about economy in relation to soil health, but this information did neither fall into the subthemes, nor occured often enough to create a new subtheme. Such gaps were then only assigned to the main overarching theme 'Economy', without further specification into one or multiple subthemes.

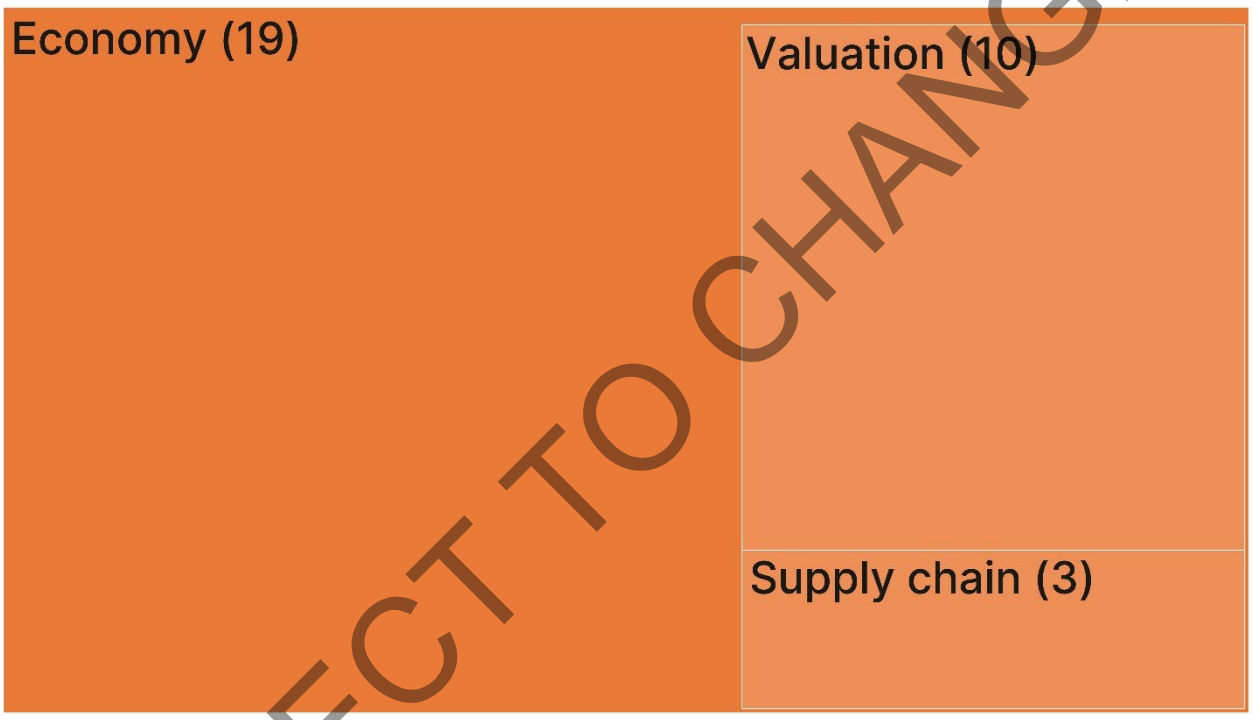

Figure 17. Hierarchy chart of the subthemes belonging to the main overarching knowledge gap theme 'Economy.' Box brightness represents the hierarchical level of the subtheme. Box size indicates the number of knowledge gaps that are allocated to each main and subtheme.

Research requirements

This overarching theme gathers approaches to acquire missing knowledge. Most of the time, what method ('tools') is necessary for obtaining the required knowledge was specified (62 references, Figure 18). To this end, observational studies were most often recommended (45 references), followed by models (21 references), experiments (20 references), theoretical frameworks (18 references) and maps (7 references). Within suggestions on how to solve knowledge gaps, spatio-temporal characteristics were frequently specified (49 references), such as the integration of context-specificity (34 references), specifics on the temporal or spatial scale (20 references) or land use types that should be considered (13 references) and of similar importance, the need for long-term research (13 references). Finally, the require type of research was often specified (44 references), of which interdisciplinary (30 references) and transdisciplinary (17 references) were more frequently mentioned. In three cases, citizen science was recommended as a way to obtain the required data, rather than as a communication strategy. Curiously, multidisciplinary approaches were not mentioned in the knowledge gap descriptions. Disciplinary approaches were assumed to be the default and hence were not specifically identified as subtheme in 'Research requirements'.

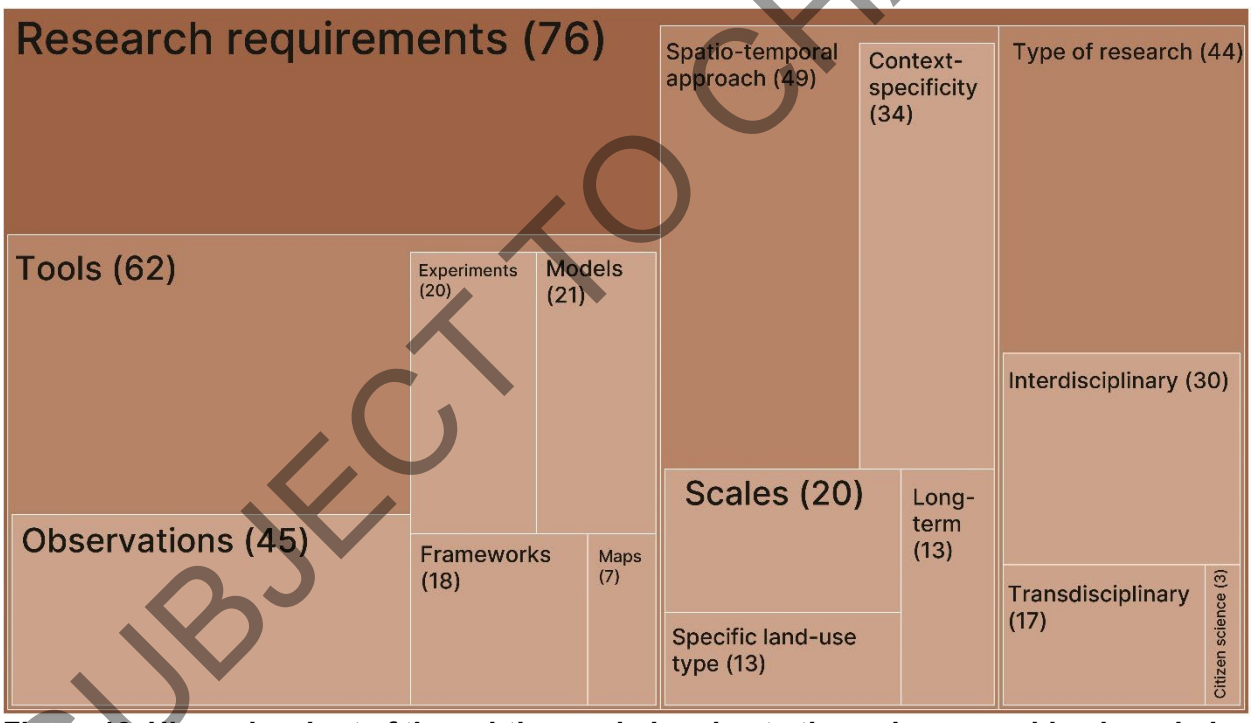

Figure 18. Hierarchy chart of the subthemes belonging to the main overarching knowledge gap theme 'Research requirements.' Box brightness represents the hierarchical level of the subtheme. Box size indicates the number of knowledge gaps that are allocated to each main and subtheme.

3.3 Strategies to overcome implementation bottlenecks

To identify the leverage point(s) that may solve knowledge gaps most effectively, the 304 individual bottlenecks were classified into overarching bottlenecks that represent different bottleneck types. Then, it was identified which bottleneck type(s) were most often hindering the solving of knowledge gaps, and which synergies and trade-offs existed in relating the overarching bottlenecks to the overarching knowledge gaps.

The thematic synthesis of 304 bottlenecks resulted in six overarching bottlenecks (for definitions see Table 9):

1) Resource limitations.
2) Complexity and/or context-dependency.
3) Lack of standardization or absence of monitoring system and/or research methods.
4) Inadequate knowledge network of soil stakeholders.
5) Inadequate attitude, focus and/or limited awareness of the importance of soil health.
6) Inadequate policy and/or governance.

Table 9. The main overarching bottlenecks across the Mission Objectives as identified from the Think Tank roadmaps with a thematic synthesis. Their definitions as used in SOLO are also presented.

Main overarching bottlenecks	Definition of the main overarching bottlenecks
Resource limitations	This overarching bottleneck indicates that certain resources are lacking for taking the required action to solve a knowledge gap. The types of missing resources vary strongly. The ones specified are a lack of adequate education, institutional barriers like limited labor capacity or lab facilities, insufficient available expertise or skill of scientists, or a generally inefficient allocation of existing resources. Other specified resources are a lack of time due to time-consuming processes and financial barriers beyond European funding for research and innovation.
Complexity and/or context-dependency	This overarching bottleneck indicates that strong complexity and/or context-dependency hinder taking the required action to solve a knowledge gap. The complexity can derive from natural, societal or social processes or structures, or from scaling issues. The context-dependency derives from the natural or societal context, or both.
Lack of standardization or absence of monitoring system and/or research methods	This overarching bottleneck indicates the absence of an adequate monitoring, reporting or verification system or adequate research method, or lack of standardization of already existing monitoring systems and methods. Such systems and methods hinder taking the required actions to solve a knowledge gap. Specified elements that require standardization include definitions, methods, indicators and benchmarks, and the organization and accessibility of data.
Inadequate knowledge network of soil stakeholders	This overarching bottleneck indicates that the network of soil stakeholders is not strong enough for taking the required action to solve a knowledge gap. In principle, soil stakeholders can include all actors that directly or indirectly influence soil health, and this theme specifies the specific disconnection between soil science and societal stakeholders, and also identifies what should be more exchanged between actors: knowledge, methods, or data.

Inadequate attitude, focus and/or limited awareness of the importance of soil health	This overarching bottleneck indicates that the attitude, focus, or general awareness on the importance of soils for actors is not adequate enough for taking the required action to solve a knowledge gap. Specific examples of an inadequate attitude include stakeholders' disinterest or conflicting interests, and a resistance to change. Examples of an inadequate focus are a lack of a holistic approach for soil health, giving soil health insufficient priority, or too much focusing on the health of soil within Europe but not outside Europe. This theme also includes the bottleneck of the presence of too diverging perceptions of stakeholders that hinder taking required actions.
Inadequate policy and/or governance	This overarching bottleneck indicates that the policy framework, its implementation through institutions and legislations, or governance structure is not adequate enough for taking the required action to solve a knowledge gap. Specific examples of issues with a policy framework include contradiction between policy instruments, ambiguous policies, and policy frameworks that do not align with the needs to improve soil health.

Most bottlenecks were related to a 'Lack of standardization or absence of a monitoring system and/or research methods', and to 'Resource limitations' beyond European funding for research or innovation (Table 10). The large number of bottlenecks of the *Desertification and land degradation* roadmap (117 out of 304 bottlenecks, Table 3) partly underlies this ranking, since the majority of its bottlenecks were assigned to these two overarching bottlenecks (Table 10). Nevertheless, all Think Tank roadmaps identified one, but usually multiple bottlenecks related to the 'Lack of standardization and/or the absence of a monitoring system or research methods'. Likewise, the 'Intrinsic complexity and context-dependency' of natural and/or societal processes and structures was hindering solving knowledge gaps of all Mission Objectives. The *Soil erosion* roadmap most often had not any bottleneck assigned to one of the overarching bottlenecks, likely because the roadmap only contained four bottlenecks.

Table 10. The number of individual bottlenecks of each Think Tank roadmap, and their totals, assigned to each overarching bottleneck (in columns).

Think Tank roadmaps	Overarching bottlenecks					
	Lack of standardization or absence of monitoring, reporting and verification system and/or research methods	Resource limitations	Complexity and/or context-dependency	Inadequate attitude, focus and/or limited awareness of the importance of soil health	Inadequate policy and/or governance	Inadequate knowledge network soil stakeholders
EU global footprint on soils	6	0	1	4	4	1
Desertification and land degradation	61	49	6	5	10	6
Soil biodiversity	3	3	7	0	1	3
Soil erosion	1	0	1	2	0	0
Soil literacy	3	11	2	10	3	2
Soil organic carbon	7	5	15	7	2	3
Soil pollution	5	11	8	7	4	2
Soil sealing and reuse urban soils	9	8	7	5	6	1
Soil structure	9	4	9	0	0	7
Total think tanks	**104**	**91**	**56**	**40**	**30**	**25**

The number of bottlenecks varied more strongly among the Think Tank roadmaps than the number of knowledge gaps (Table 3). Nevertheless, a comparable trend was seen when correcting for the different number of bottlenecks per Think Tank roadmap (Table 11). The three most often occurring types of bottlenecks remained related to the 'Standardization and/or absence of a monitoring system or research methods', 'Resource limitations', and 'Complexity and/or context-dependency' (Table 11). There were no strong trade-offs observed among solving the different bottleneck types, as they were all related to seven or more Mission Objectives

Table 11. Percentage of individual bottlenecks of each Think Tank roadmap assigned to each overarching bottleneck (in columns), relative to the total number of bottlenecks present in the Think Tank roadmap (Table 1). The lowest row presents the average percentage of individual bottlenecks that were assigned to each overarching bottleneck.

Think Tank roadmaps	Overarching bottlenecks					
	Lack of standardization or absence of monitoring, reporting and verification system and/or research methods	Resource limitations	Complexity and/or context-dependency	Inadequate attitude, focus and/or limited awareness of the importance of soil health	Inadequate policy and/or governance	Inadequate knowledge network soil stakeholders
EU global footprint on soils	40	0	7	27	27	7
Desertification and land degradation	52	42	5	4	9	5
Soil biodiversity	19	19	44	0	6	19
Soil erosion	25	0	25	50	0	0
Soil literacy	11	41	7	37	11	7
Soil organic carbon	18	13	38	18	5	8
Soil pollution	19	41	30	26	15	7
Soil sealing and reuse urban soils	28	25	22	16	19	3
Soil structure	33	15	33	0	0	26
Average think tanks	**27**	**22**	**23**	**20**	**10**	**9**

We then related the different bottleneck types to the nine overarching knowledge gaps that were found across Mission Objectives. All bottlenecks appeared to related to at least five of the six overarching knowledge gaps, suggesting synergies, rather than trade-offs when solving them (Figure 19). Moreover, all overarching knowledge gaps were related to all bottleneck types. The only exception was that the 'Impact of soil health on society' related to only three overarching bottlenecks (Figure 19).

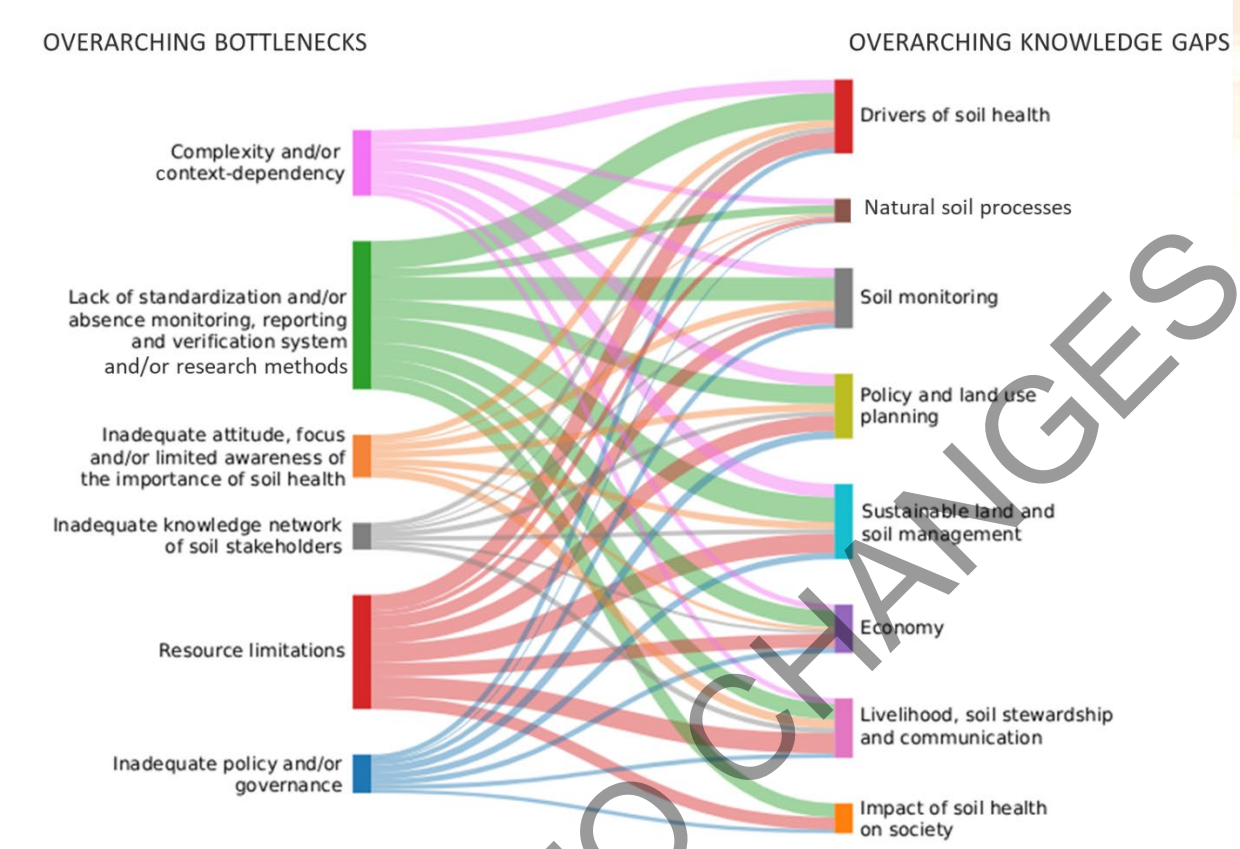

Figure 19. The number of relationships between overarching bottlenecks (left, see Table 9 for their definitions) and overarching knowledge gaps (right, see Table 6 for their definitions) found across all Mission Objectives.

The 'Lack of standardization or absence of a monitoring system and/or research methods' was the most frequently occurring bottleneck type, and was also strongly related to all overarching knowledge gaps (Figure 19). A similar trend was observed for 'Resource limitations', which was clearly linked to all knowledge gaps (Figure 19).Although adressing the overarching knowledge gap the 'Impact of soil health on society' was only hindered by three bottleneck types, two of these bottlenecks were the most frequently occurring ones mentioned above. Therefore, research leading to enhanced standardization of monitoring systems and/or research methods may provide leverage points for both the general and more specific overarching knowledge gaps, as well as for all Mission Objectives. Overcoming resource limitations beyond European funding provides another important leverage point, for instance via improving soil education, increasing the efficiency or the allocation of existing resources and reducing institutional barriers. In section 4.3.2, we further explore the narratives of these two key overarching bottleneck themes via analysing their subthemes in a similar manner as done for the knowledge gaps.

3.3.1 Narrative overarching key bottlenecks

Absence or lack of standardization in a monitoring system and/or research methods

A majority of bottlenecks evolved around the standardization of a monitoring framework or its specific elements (i.e., definitions, data, methods, indicators and benchmarks, 74 references) rather than a pure lack of monitoring system (35 references) or adequate research methods (8 references, Figure 20). The most important element that needs to be standardized was data organization and accessibility (34 references), followed by applied monitoring methods (22 references), definitions within and beyond the monitoring system (11 references) and lastly indicators and benchmarks (5 references).

Interestingly, soil monitoring was both mentioned in this overarching bottleneck theme and the overarching knowledge gap of 'soil monitoring' (Figure 19). On average, over half of the knowledge gaps were assigned to the overarching theme 'Soil monitoring' (Table 8), and all of them were strongly related to soil monitoring as part of this overarching bottleneck (Figure 19). This means that the development of a harmonized monitoring system and adequate research methods requires research to optimize efficiency and/or efficacy.

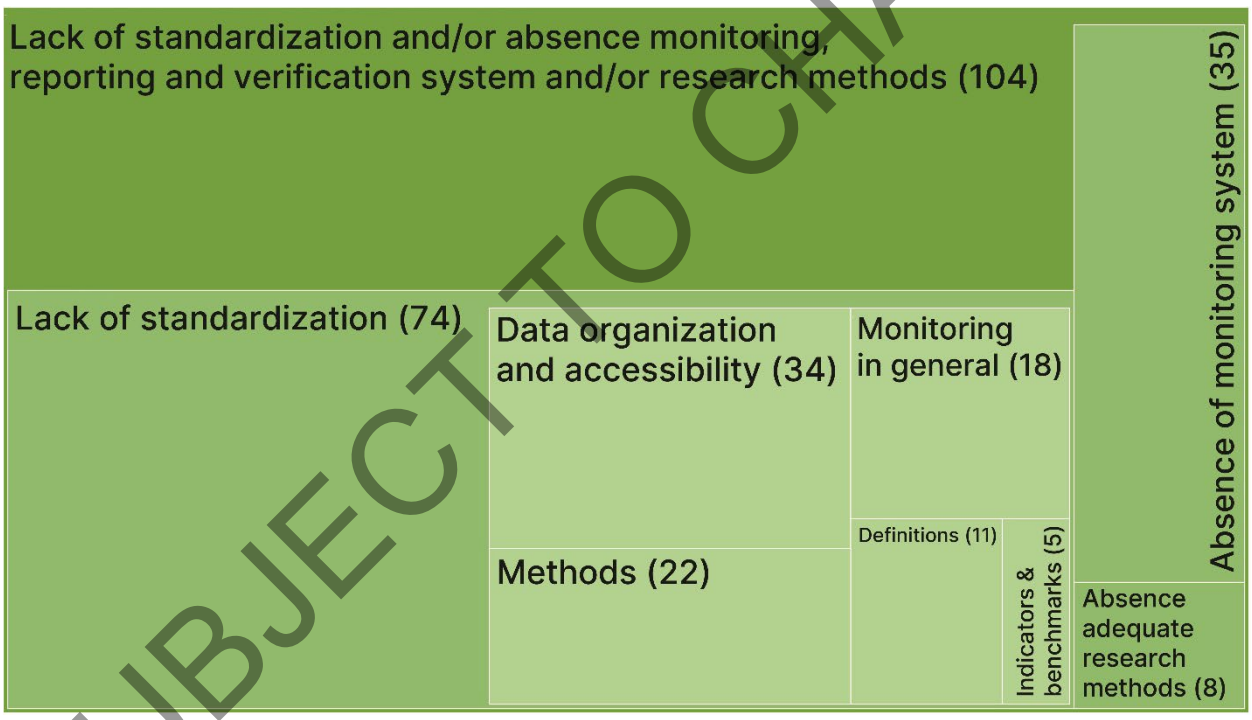

Figure 20. Hierarchy chart of the subthemes belonging to the main overarching bottleneck theme 'Absence or lack of standardization in a monitoring system and/or research methods.' Box brightness represents the hierarchical level of the subtheme. Box size indicates the number of knowledge gaps that are allocated to each main and subtheme.

Resource limitations

Resource limitations include all types of resources except European funding for research and innovation. Most bottlenecks involve financial barriers beyond EU funding, e.g. knowledge gaps requiring investments from the private sector (30 references, Figure 21). Time constraints was another important resource, due to time-consuming processes, not only in the soil ecosystem, but also for instance in society and in applying analytical methods (23 references). Other important limitations included a lack of adequate soil education of teachers, land managers or citizens (12 references) and institutional barriers such as limited lab capacity or bureaucratic contraints (10 references). Further resource limitations were allocated to this overarching bottleneck, such as an inefficient allocation of already existing resources or limited available scientific expertise, but these resource types were too infrequent to constitute a separate subtheme.

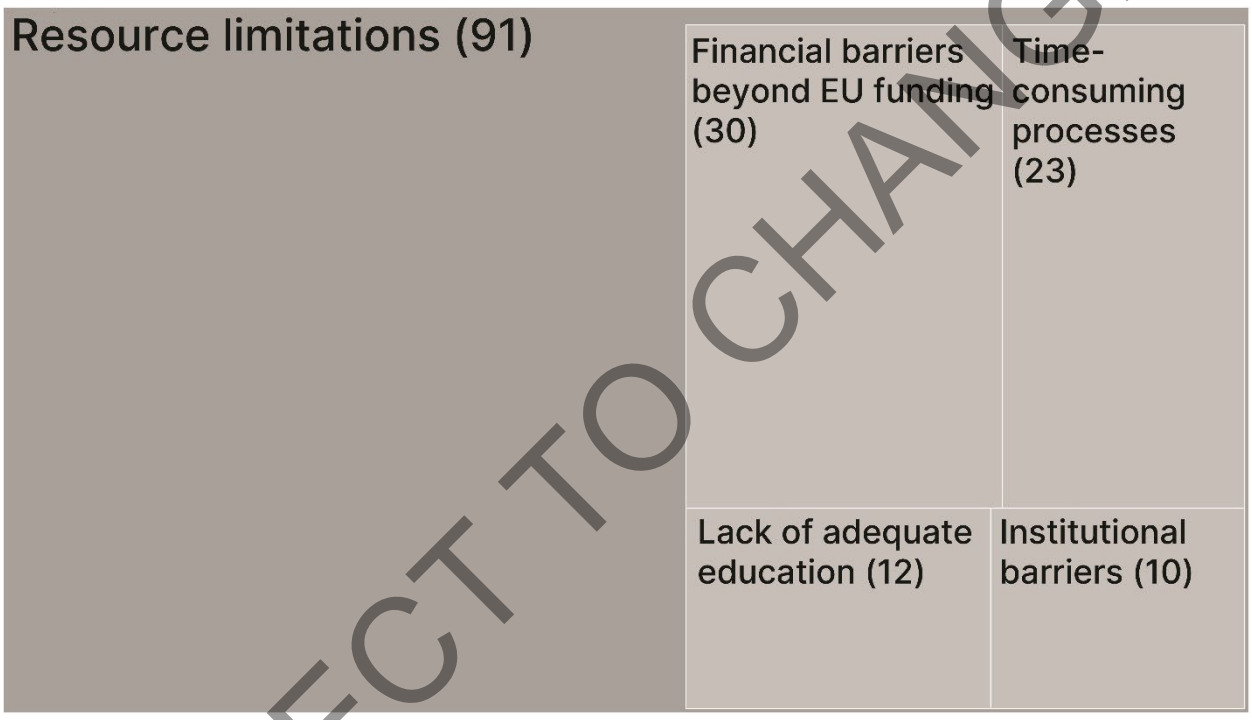

Figure 21. Hierarchy chart of the subthemes belonging to the main overarching bottleneck theme 'Resource limitations.' Box brightness represents the hierarchical level of the subtheme. Box size indicates the number of knowledge gaps that are allocated to each main and subtheme.

4 Synergies and trade-offs across regions

4.1 Methodology on finding synergies and trade-offs across regions

Synergies and trade-offs across regions were identified from the regional inputs that were collected during the Soil Week events and Regional Node workshops of 2023-2025, drawing from D4.7. In these activities, we brought together various local actors that are all related to the use of land and the health of soil. These actors consist of civil society, industry, policy makers, practitioners, sector organizations and members of industry (D4.7). The events have resulted into regional reports that we use here to search for synergies and trade-offs across regions. Synergies occur when a single research or innovation action may help to solve multiple knowledge gaps across various regions. Trade-offs occur when addressing knowledge gaps from one region limits the ability to solve knowledge gaps in a different region. The understanding of synergies and trade-offs across regions hence takes a slightly different shape than the one described for the Think Tanks.

The size of a region depends on its definition, and can range from local (kilometre-scale) till European-wide continental scale. In SOLO, we used Regional Nodes and Soil Weeks to collect regional inputs at three different spatial scales:

- A region of approximately 30x30 km, the scale at which the Regional Nodes operate.
- A country, the scale at which the Soil weeks were mostly operating.
- A European macro-region, by aggregating the results of the Soil Weeks at country level into four EU macro-regions:
  - South: Spain, Portugal, Italy, Greece.
  - North: Finland, Norway, Sweden.
  - East: Hungary, Bulgaria.
  - West: Netherlands, Belgium, Germany.

We allocated the specific knowledge gaps that were identified during the Soil Week events and Regional Node workshops to the nine overarching knowledge gaps across Mission Objectives that were identified from the Think Tank roadmaps (see section *3. Synergies and trade-offs across Mission Objectives*). We then analysed the synergies and trade-offs of the knowledge gaps across regions separately for the Soil Weeks and for the Regional Nodes, because the Regional Node workshops allowed a more in-depth identification of the knowledge gaps compared to the Soil Week events. Moreover, the Soil Weeks covered more adequately all Mission Objectives than the Regional Nodes. Finally, we grouped the results of the number of gaps allocated to the nine overarching knowledge gaps by the three different spatial scales (region, country, macro-region)

4.2 Specification and number of knowledge gaps of Soil Weeks and Regional Nodes

A total of 259 knowledge gaps were identified in the Soil Week events across the 12 countries and across Mission Objectives (Table 12). The number of knowledge gaps varies widely per country, from 8 (Belgium, Germany and Spain) to 72 (Norway). Nonetheless, most countries identified between 10 and 30 knowledge gaps. There were more knowledge development gaps identified than knowledge application gaps, but the difference is relatively minor (87 and 76, respectively, Table 12), indicating that soil weeks identify a relatively comparable need for generating new and applying already existing information. This observation is further supported by 33 gaps being categorized as both knowledge development gaps and knowledge application gaps, mostly deriving from the Soil Weeks of Hungary and the Netherlands (10 and 9 gaps

assigned to this category, respectively, Table 12). The precise balance between knowledge development gaps versus knowledge application gaps differs per country, with 6 countries having more knowledge development gaps than knowledge application gaps, and 6 countries the other way around (Table 12). It is also relevant to note that 63 knowledge gaps were left uncategorized, almost all (62) gaps deriving from Norway. The typology of the knowledge gaps of the Soil Weeks was similar to those of produced by the Think Tanks, with the majority of the gaps characterized as development gaps, followed by application gaps and, finally, application plus development gaps (Table 2, Table 12).

Table 12. The total number of prioritized knowledge gaps that each country has identified during the Soil Week events (upper 12 rows), and/or Regional Node workshops (lower 4 rows) in the years 2023-2025, and 2024-2025, respectively. These prioritized knowledge gaps are further classified as knowledge development gaps (KDG), knowledge application gaps (KAG), or an equal share of both categories (both KDG and KAG).

Country	Total of knowledge gaps	Total of uncategorized knowledge gaps	Knowledge development gap (KDG)	Knowledge application gap (KAG)	Both KDG and KAG
		Soil weeks			
Belgium	8	0	5	3	0
Bulgaria	18	0	8	10	0
Finland	12	0	6	4	2
Germany	8	0	2	5	1
Greece	17	0	9	5	3
Hungary	27	1	6	10	10
Italy	12	0	1	8	3
Netherlands	41	0	13	19	9
Norway	72	62	6	1	3
Portugal	26	0	21	5	0
Spain	8	0	4	4	0
Sweden	10	0	6	2	2
Total	**259**	**63**	**87**	**76**	**33**
		Regional nodes			
Hungarian forests	53	0	7	23	23
Portuguese Montádo	25	0	10	12	3
Netherlands mixed farming	29	3	6	11	9
Swedish urban-rural gradient	25	0	11	9	5
Total	**132**	**3**	**34**	**55**	**40**

As for the four Regional Nodes, it was possible to identify a total of 132 knowledge gaps, ranging from 25 to 53 per Regional Node. The majority of the gaps was categorized as knowledge application gaps (55), and there was also a high number of gaps that are both knowledge

development and knowledge application gaps (40). Only 3 knowledge gaps were not categorized. Compared to the Soil Weeks, the range of identified gaps among the Regional Nodes was narrower than among the Soil Weeks, which were carried out in twelve countries (including those four that had Regional Node workshops) and there were considerably fewer uncategorized gaps. The different findings between Soil Weeks and Regional Nodes result from the methodologies and guidelines that were established for the two activities: where Regional Node workshops were similarly implemented in all four regions, there was considerably more diversity in the way how the Soil Week events were set up. The different nature of the two activities is also reflected in the higher importance of the knowledge application gaps for the Regional Nodes than the Soil Weeks, which appears to be caused by the more regional and practice-oriented focus of the Regional Nodes.

4.3 Synergies and trade-off across regions based on Soil Week events and Regional Node workshops

4.3.1 Soil Week events

Three synergies were identified by comparing the common-ground of the overarching knowledge gaps of the Soil Weeks and Think Tanks:

1) Knowledge gaps about 'Sustainable land and soil management' were identified in all countries that organized Soil Week events (Table 13). Hence, actions that aim to (further) develop, evaluate and implement strategies and practices for (more) sustainable land and soil management are expected to be relevant for most, if not all, European countries. The same Europe-wide relevance applied to actions about the involved decision-making processes related to soil and land management.
2) The knowledge gaps of all countries were allocated to at least 5 of the 9 overarching knowledge gaps (Table 13). Hungary, Norway and Portugal even identified gaps in all overarching knowledge gaps.
3) Interestingly, 'Economy' is the least relevant overarching knowledge gap across countries, in spite of the Soil Week partners' perception of its transversal importance (see Deliverable D4.7). All countries that organized Soil Week events attributed 13% or less of their knowledge gaps to 'Economy', except for Germany (38%, Table 14).

A potential trade-off could be formed by Germany, Spain and Finland, since the knowledge gaps of these countries were allocated to the lowest number of overarching knowledge gaps (5 out of 9). However, this finding might be due to that the results of the 2025 Soil Week events of Spain and Finland still are to come (see Deliverable D4.7). Contrary to the Think Tanks, in which it was possible to clearly identify trade-offs between Mission Objectives, Soil Week results did therefore not yet allow for such concluding remarks. This will be possible once all results Soil Week events have come in (upcoming D4.5, M48).

Comparing the importance of the overarching knowledge gaps across Mission Objectives and countries, hence comparing the results for the Think Tank roadmaps with those for the Soil Weeks, we observe one more important synergy:

- 'Drivers of soil health', 'Sustainable land and soil management' and 'Soil monitoring' are the three most important overarching knowledge gaps both across Mission Objectives (Table 7) and across countries (Table 13).

Further comparing of the synergies and trade-offs across Mission Objectives with those of the Soil Week countries showed that knowledge gaps on 'Livelihood, soil stewardship and communication' are more relevant across countries than across Mission Objectives. Moreover, 'Research requirements' appear to be much less relevant across Soil Week countries than across Mission Objectives. This means that Soil Weeks provide more information about what knowledge is lacking, and less information about what type of approach in research or innovation is missing. Both results are in line with the more diverse stakeholder pool, type of events in which the input was collected (e.g., outreach activities), and less in-depth input on research needs of Soil Weeks compared to Think Tanks. Moreover, the involved regional actors may be more in the action modus and may therefore mostly want to have a solution, and may therefore think less of things that need time to be studied.

Table 13. Number of individual knowledge gaps of all Soil Weeks that have thus far taken place in each country, based on the assignment to the overarching knowledge gaps (in columns). The lowest row presents the total number of individual knowledge gaps of every overarching knowledge gap.

Country	Overarching knowledge gaps								
	Drivers soil health	Sustainable land and soil management	Soil monitoring	Policy and land use planning	Livelihood, soil stewardship and communication	Impact of soil health on society	Natural soil processes	Economy	Research requirements
Belgium	1	1	2	1	3	1	0	1	2
Bulgaria	2	2	5	1	7	0	0	1	4
Finland	3	3	5	0	0	1	1	0	0
Germany	0	2	0	3	2	0	0	3	2
Greece	2	1	6	3	6	0	1	0	1
Hungary	3	10	6	5	8	4	1	2	1
Italy	1	1	1	4	5	2	3	0	1
Netherlands	9	12	5	1	6	2	12	0	0
Norway	32	14	13	4	5	7	14	1	6
Portugal	8	1	9	2	3	1	3	1	4
Spain	0	4	1	1	1	1	0	0	0
Sweden	4	4	0	1	1	4	1	1	0
Total	**65**	**55**	**53**	**26**	**47**	**23**	**36**	**10**	**21**

Table 14. Percentage of individual knowledge gaps of all Soil Weeks that have thus far taken place in each country, based on the assignment to the overarching knowledge gaps (in columns) relative to the total number of knowledge gaps per country. The lowest row presents the average percentage of individual knowledge gaps that were assigned to each overarching knowledge gap.

Country	Overarching knowledge gaps								
	Drivers soil health (%)	Sustainable land and soil management (%)	Soil monitoring (%)	Policy and land use planning (%)	Livelihood, soil stewardship and communication (%)	Impact of soil health on society (%)	Natural soil processes (%)	Economy (%)	Research requirements (%)
Belgium	13	13	25	13	38	13	0	13	25
Bulgaria	11	11	28	6	39	0	0	6	22
Finland	25	25	42	0	0	8	8	0	0
Germany	0	25	0	38	25	0	0	38	25
Greece	12	6	35	18	35	0	6	0	6
Hungary	11	37	22	19	30	15	4	7	4
Italy	8	8	8	33	42	17	25	0	8
Netherlands	22	29	12	2	15	5	29	0	0
Norway	44	19	18	6	7	10	19	1	8
Portugal	31	4	35	8	12	4	12	4	15
Spain	0	50	13	13	13	13	0	0	0
Sweden	40	40	0	10	10	40	10	10	0
Average	**18**	**22**	**20**	**14**	**22**	**10**	**9**	**7**	**9**

To try and identify larger regional trends, we also analysed the results of the Soil Weeks by aggregating the Soil Week countries into four macro-regions (i.e., North, South, East, West). We then observed the following three synergies in the macro-regions:

1) All overarching knowledge gaps were represented across the four macro-regions of the Soil Weeks (Table 15), suggesting that synergistic actions for solving each overarching knowledge gap are relevant for the whole of Europe.
2) The three most relevant overarching knowledge gaps for all Soil Week macro-regions were 1) 'Drivers of soil health; 2) 'Sustainable land and soil management'; and 3) 'Soil monitoring' (Table 15). These three overarching knowledge gaps were also the most important for all Mission Objectives (Table 8).
3) The overarching knowledge gap 'Livelihood, soil stewardship and communication' was equally important as 'Soil monitoring' for the four macro-regions, considering the number of allocated knowledge gaps that were associated to this them relative to the total number of gaps (Table 8). This overarching knowledge gap was especially relevant for *Soil Literacy*, *Desertification and land degradation* and *Soil erosion*, but less so for the other Mission Objectives.

Even though no strong trade-offs could be identified between the different macro-regions, the North seems to be the macro-region that differed most from other macro-regions. 'Drivers of soil health' was clearly the most relevant overarching gap in the North, and more important than for the other macro-regions (Table 16). The 'Impact of soil health on society' also seemed to be more relevant to the North than to any other region (Table 15). On the other hand, gaps on 'Policy and land use planning', and 'Livelihood, soil stewardship and communication' were much less relevant in the North than in the other macro-regions (Table 15, Table 16).

This analysis shows that all the overarching knowledge gaps are relevant across macro-regions and that some trade-offs, in spite of dimly identifiable, are found through this macro-regional

approach. This indicates that it is worth exploring the connection between overarching knowledge gaps and macro-regions, which is currently being planned for the fourth and final Soil Week in 2026.

Table 15. Number of individual knowledge gaps in each overarching knowledge gap in the macro-regions, based on Soil Weeks, as far as completed. The lowest row provides the totals.

Macro-region	Overarching knowledge gaps								
	Drivers soil health	Sustainable land and soil management	Soil monitoring	Policy and land use planning	Livelihood, soil stewardship and communication	Impact of soil health on society	Natural soil processes	Economy	Research requirements
North (Finland, Norway, Sweden)	39	21	18	5	6	12	16	2	6
South (Spain, Portugal, Italy, Greece)	11	7	17	10	15	4	7	1	6
East (Hungary, Bulgaria)	5	12	11	6	15	4	1	3	5
West (Netherlands, Belgium, Germany)	10	15	7	5	11	3	12	4	4
Total	**65**	**55**	**53**	**26**	**47**	**23**	**36**	**10**	**21**

Table 16. Percentage of individual knowledge gaps in the macro-regions in which all Soil Weeks have thus far taken place, based on the assignment to the overarching knowledge gaps (in columns) relative to the total number of knowledge gaps per macro-region. The lowest row presents the average percentage of individual knowledge gaps that were assigned to each overarching knowledge gap.

Macro-region	Overarching knowledge gaps								
	Drivers soil health (%)	Sustainable land and soil management (%)	Soil monitoring (%)	Policy and land use planning (%)	Livelihood, soil stewardship and communication (%)	Impact of soil health on society (%)	Natural soil processes (%)	Economy (%)	Research requirements (%)
North (Finland, Norway, Sweden)	41	22	19	5	6	13	17	2	6
South (Spain, Portugal, Italy, Greece)	17	11	27	16	24	6	11	2	10
East (Hungary, Bulgaria)	11	27	24	13	33	9	2	7	11
West (Netherlands, Belgium, Germany)	18	26	12	9	19	5	21	7	7
Average	**22**	**22**	**21**	**11**	**21**	**8**	**13**	**4**	**9**

4.3.2 Regional Node workshops

Three synergies were identified by comparing the common-ground of the overarching knowledge gaps of the Soil Weeks and Think Tanks:

1) All overarching knowledge gaps were relevant for all four Regional Nodes, except that 'Natural soil processes' were not mentioned by the Swedish Regional Node (Table 17).
2) For all Regional Nodes, the two most relevant knowledge gaps were 'Sustainable land and soil management', and 'Livelihood, soil stewardship and communication' (Table 17, Table 18).
3) 'Soil monitoring' and 'Policy and land use planning' were the next two relevant overarching knowledge gaps (Table 17, Table 18).

The most important overarching knowledge gaps for the regions demonstrate a practical orientation of the users in the Regional Nodes. The strong unanimity in synergies among regions appears to go hand in hand with few indications of trade-offs across regions. Therefore, the insights from the Regional Nodes compare well with those from the Soil Weeks.

Interestingly, the most important overarching knowledge gaps of the Regional Nodes differ from those in the Think Tanks. In the Regional Nodes, the 'Drivers of soil health' are less frequently mentioned (on average 12% of all knowledge gaps, Table 18) than in the Think Tanks (on average 52%, Table 8). In the Regional Nodes, 'Livelihood, soil stewardship and communication' was more important than in the Think Tanks (Table 8, Table 18). Finally, Regional Nodes identified fewer knowledge gaps related to 'Research requirements' than Think Tanks. Therefore, discussions in the regions are focussing more on the missing knowledge and innovations rather than on the precise research needs, so that researchers need to translate questions from practice into a actionable research questions and approaches

There were also similarities between the results from the Regional Nodes and those of the Think Tanks. For instance, both Regional Nodes and Think Tanks identified that the two least relevant overarching knowledge gaps were 'Natural soil processes' and 'Economy'. Moreover, 'Sustainable land and soil management' was among the most important three themes for both Regional Nodes, Think Tanks, and even for Soil Weeks. 'Soil monitoring' and 'Policy and land planning' were also in the top four of knowledge gaps identified by Regional Nodes, Soil Weeks, and Think Tanks.

Integrating the results of Think Tanks, Regional Nodes and Soil Weeks leads to the identification of three overarching knowledge gaps with a high potential synergism and high relevance for solving knowledge gaps in all Mission Objectives at all spatial scales, from region to country to macro-region:

1) Sustainable land use and soil management.
2) Soil monitoring.
3) Policy and land planning.

'Drivers of soil health' provide most synergies across Mission Objectives, but was not necessarily perceived as most relevant for the regions. 'Livelihood, soil stewardship and communication' was relevant for all regions, Soil week countries, and macro-regions. This gap was also relevant for especially the Mission Objectives of *Soil Literacy*, *Desertification and land degradation* and *Soil erosion*, but less so for the other Mission Objectives

Table 17. Number of individual knowledge gaps of all Regional Node workshops that have thus far taken place in each region as assigned to each overarching knowledge gap (in columns). The lowest row presents the totals.

Region	Overarching knowledge gaps								
	Drivers soil health	Sustainable land and soil management	Soil monitoring	Policy and land use planning	Livelihood, soil stewardship and communication	Impact of soil health on society	Natural soil processes	Economy	Research requirements
Keszthely Hills Region (Hungarian forests)	13	18	17	5	10	11	9	5	14
Mértola (Portuguese Montádo)	1	5	4	6	11	4	1	6	3
Achterhoek (Netherlands mixed farming)	5	7	4	1	14	4	5	1	7
Southwest Skåne (Swedish urban-rural gradient)	1	16	6	13	5	1	0	2	3
Total	**20**	**46**	**31**	**25**	**40**	**20**	**15**	**14**	**27**

Table 18. Percentage of individual knowledge gaps of all Regional Node workshops that have thus far taken place in each region, based on the assignment to the overarching knowledge gaps (in columns) relative to the total number of knowledge gaps per. The lowest row presents the average percentage of individual knowledge gaps that were assigned to each overarching knowledge gap

Region	Overarching knowledge gaps								
	Drivers soil health (%)	Sustainable land and soil management (%)	Soil monitoring (%)	Policy and land use planning (%)	Livelihood, soil stewardship and communication (%)	Impact of soil health on society (%)	Natural soil processes (%)	Economy (%)	Research requirements (%)
Keszthely Hills Region (Hungarian forests)	25	34	32	9	19	21	17	9	26
Mértola (Portuguese Montádo)	4	20	16	24	44	16	4	24	12
Achterhoek (Netherlands mixed farming)	17	24	14	3	48	14	17	3	24
Southwest Skåne (Swedish urban-rural gradient)	4	64	24	52	20	4	0	8	12
Average	**12**	**36**	**21**	**22**	**33**	**14**	**10**	**11**	**19**

4.4 Project workflow as a mechanism for roadmap regionalization

The workflow between Think Tanks, Regional Nodes, Soil Weeks and WP3 forms a mechanism to regionalize the Think Tank roadmaps, supporting the integration of regional inputs in these roadmaps continuously across the span of the project (Figure 2). The regional inputs are exchanged shortly after regional activities have taken place (e.g., Soil Week partners send the relevant Think Tanks their event report one month after the event was held), in a continuous and organic manner. As such, it is difficult to trace to what extent regional inputs are integrated in the Think Tank roadmaps through the workflow. To assess this, Think Tank leaders were asked to fill in a survey specifying if and how that integration took place. Again, a distinction was made between the input provided by the Soil Weeks and by the Regional Nodes.

Soil Weeks

The large majority of the Think Tanks have integrated Soil Week input in their roadmaps (8 out of 9), thereby confirming that the workflow contributed to the regionalization process (Figure 22).

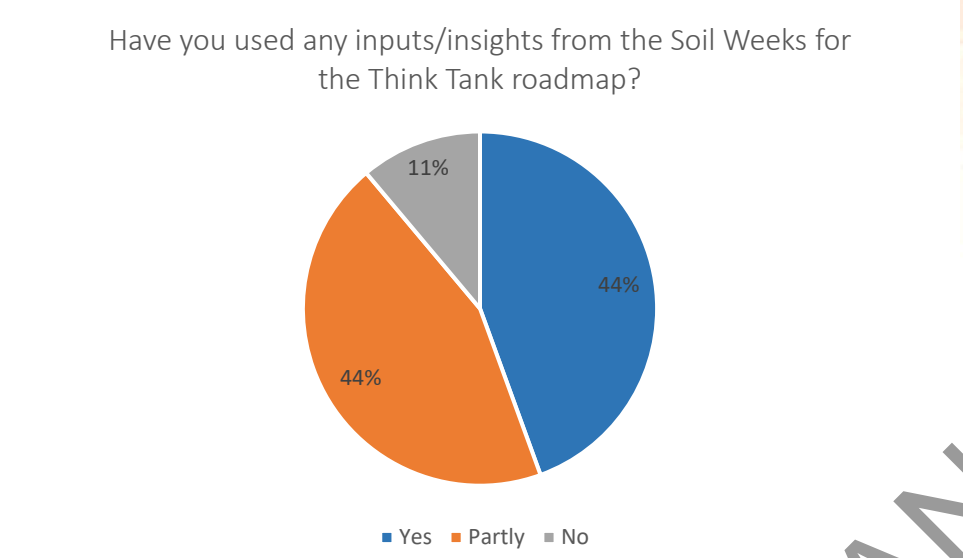

Figure 22. Percentage of Think Tanks that have used regional inputs provided by the Soil Weeks

Regional inputs from Soil Weeks were mostly used as general inspiration for the Think Tank roadmaps, and as validation of the different elements of the Think Tank roadmaps (i.e., knowledge gap, bottleneck, action, Figure 23). Three Think Tank leaders mentioned that they could almost directly include some of the regional elements in their roadmaps. Interestingly, the most useful element for the Think Tanks were the knowledge gaps (for 7 Think Tanks), followed equally by the bottlenecks and actions (for 5 Think Tanks).

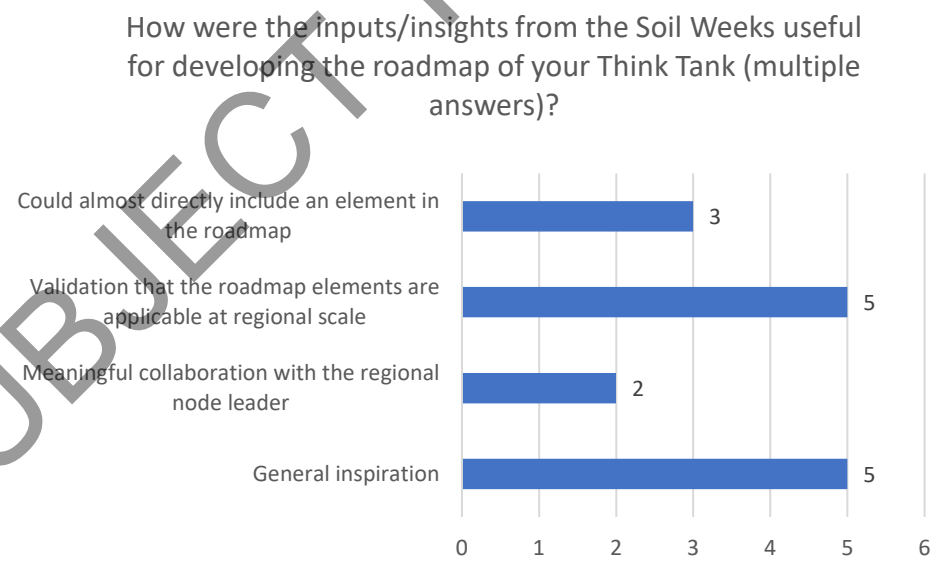

Figure 23. Type of use given by the Think Tanks to the regional input provided by the Soil Weeks

Regional Nodes

Five Think Tanks have used input from the Regional Nodes to a certain extent, four Think Tanks have not used any input at all (Figure 24).

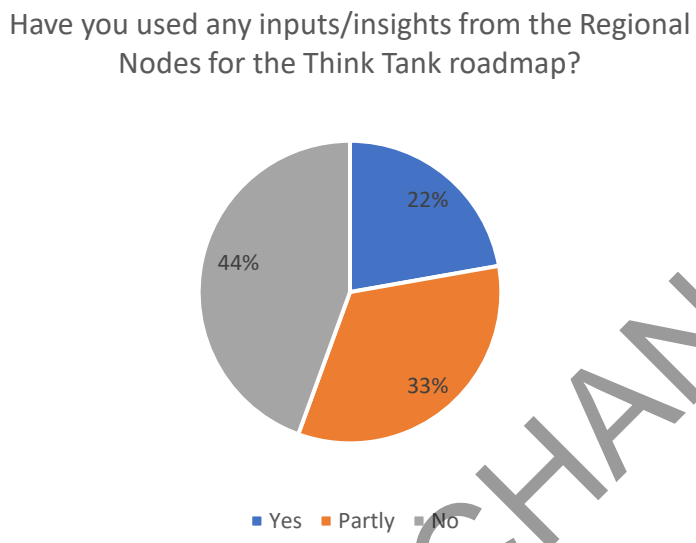

Figure 24. Percentage of Think Tanks that have used regional input provided by the Regional Nodes

Input provided by the Regional Nodes was mostly used by the Think Tanks as general inspiration for their roadmaps (Figure 25). Two Think Tank leaders have also been able to validate that their roadmap elements were applicable at the regional scale.

The most useful elements were both the knowledge gaps and the actions, mentioned by two Think Tanks as relevant. Actions were only mentioned as relevant by one Think Tank.

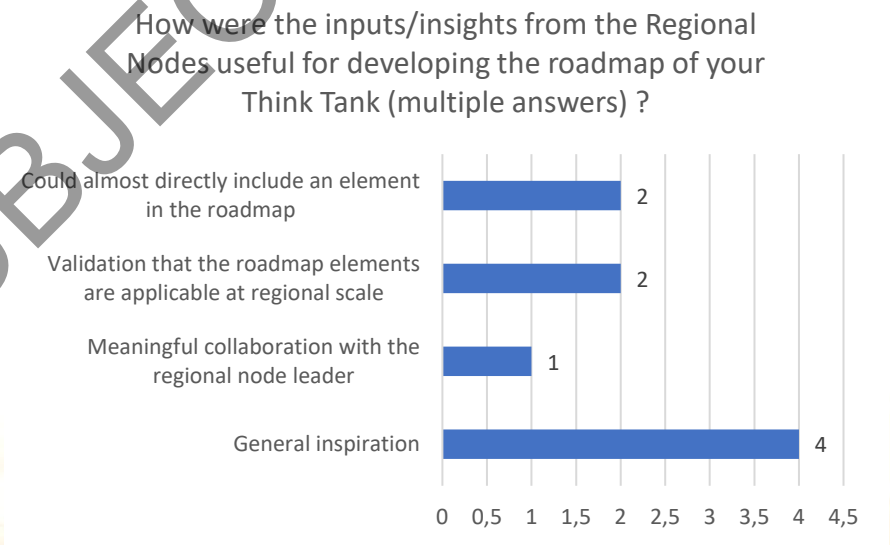

Figure 25. Type of use given by the Think Tanks to the regional input provided by the Regional Nodes

Overall analysis

Think Tanks have clearly integrated more input from the Soil Weeks than from the Regional Nodes. This could be explained by the sheer fact that more Soil Week outputs have been produced. Yearly, more than one Soil Week event addresses each Mission Objective, always collecting identified knowledge gaps, bottlenecks and actions. On the other hand, each Regional Node focuses specifically on the 3 priority Mission Objectives and, due to the workshop structure, input is gathered sequentially, meaning that only 1 of the 4 workshops has been specifically dedicated to identifying knowledge gaps, or actions. For instance, the *Soil biodiversity* Think Tank has received regional input from 10 times Soil Week events and 3 Regional Node workshops, being the the most covered Mission Objective by both Soil Weeks and Regional Nodes. Another reason could be that all Think Tank leaders have organized a Soil Week event that aligned to the Mission Objective of their think tank (see D4.7).

Think Tanks could mostly use the regional inputs in their roadmaps for general inspiration and for validation of the different roadmap elements, especially knowledge gaps, at the regional scale. For this result, it did not matter whether the regional inputs derived from Regional Nodes or from Soils Weeks

In spite of the difficulty to track this ongoing and organic integration of knowledge, the survey's results corroborate that the workflow is being effective in the regionalization process of the Think Tank roadmaps.

5 Conceptual framework on the required societal changes for improving European soil health

During the SOLO project meeting in Lund, SOLO partners concluded that the bottom-up thematic synthesis would benefit from a conceptual framework that is grounded in scientific literature. This framework should allow placing the SOLO roadmaps in a broader societal context and support the integration of the Think Tank roadmaps and regional inputs deriving from the Regional Nodes and Soil Weeks. A top-down approach was considered helpful to identify the need for research on societal changes to improve soil health. Important components of this conceptual framework are the specification of a timeline for the various actions of research and innovation, as well as of the expected outputs and outcomes leading to the societal transformations towards a Europe with healthy soils. We reviewed scientific literature on transformative change and the role of different actors, including the changes that these actors need to undergo themselves to contribute significantly to the change. We selected the conceptualization of transformative change factors which mostly demonstrated explanatory value in relation to changes in soil management ((El Bilali, 2020; Frantzeskaki and de Haan, 2009; Linnér and Wibeck, 2021, 2020; Vermunt et al., 2022; Visser et al., 2019; Wieczorek and Hekkert, 2012)). The obtained insights were coupled to decision-making processes involving the different actors at multiple, often nested, scales (Morelli et al., 2022; Shahsavarani and Azad Marz Abadi, 2015).

5.1 The need for a societal transformation to improve soil health in Europe

The envisioned impact of SOLO is to *improve the soil research and innovation agenda for an efficient use of knowledge in decision-making to achieve a 100% healthy soil status in Europe by 2050.* Decisions that influence soil health are made across all levels of society, and they occur at different scales. For instance, daily consumers' choices influence product supply chains that in the end affect land use and soil management, and therefore soil health. Soil practitioners' decisions on e.g. weed, pest, and crop management directly affect soil health. Citizens' voting behaviour influences policy constellations, influencing decisions in developing policy and jurisdiction that affect soil health. These examples illustrate how a wide range of stakeholders are directly and indirectly involved in societal processes that affect soil health.

The previous and current structure and functioning of European society has not prevented the degradation of 60-70% of the soils to an unhealthy status (Panagos et al., 2024). Ensuring that all European soils have a healthy status by 2050 therefore requires a fundamental and sustained transformation of the bio-physical and socio-economic aspects of European society (Visser et al., 2019). Such a transformation requires understanding of the different elements that constitute and influence societal functioning. The main three elements that form a society are its culture, structure and practices (Frantzeskaki and de Haan, 2009; Loorbach et al., 2015):

- Culture includes the norms, values and ethics of actors that underlie rules, constitutions, perceptions, beliefs and patterns of behaviour (Frantzeskaki and de Haan, 2009).
- Structural elements include for instance technological and knowledge infrastructures, the configuration of the market, and formal institutions such as rules and laws (Frantzeskaki and de Haan, 2009; Vermunt et al., 2022; Wieczorek and Hekkert, 2012).
- Practices derive from anticipating and handling with everyday needs and are defined by the available natural resources, knowledge capital and technology (Frantzeskaki and de Haan, 2009).

A societal transformation thus involves changing the culture, structure and practices of a society, requiring a wide array of political, technological, economic, social and environmental processes

(Linnér and Wibeck, 2020). To develop concrete and meaningful research and decision-making, the required transformation(s) need to be further characterized. The most important questions include (Linnér and Wibeck, 2020):

- What aspects of society are addressed: society as a whole, or a specific element of society?
- How should these aspects change, what type of change is needed?
- Within what time-frame can, or should, these changes take place?

These three questions specify the required societal transformative changes including their time frame to achieve 100% healthy soil status in EU and guided the development of a conceptual model, worked out in 5.2.

5.2 SOLO's framework on the required changes to improve soil health in EU

To structure and specify the required societal transformations to improve soil health in EU, Figure 26 presents a conceptual framework based on Linnér and Wibeck (2020) and further developed using literature on societal transitions (Frantzeskaki and de Haan, 2009; Loorbach et al., 2015; Vermunt et al., 2022) and the Theory of Change (Conservation Measures Partnership, 2020; Mayne, 2017).

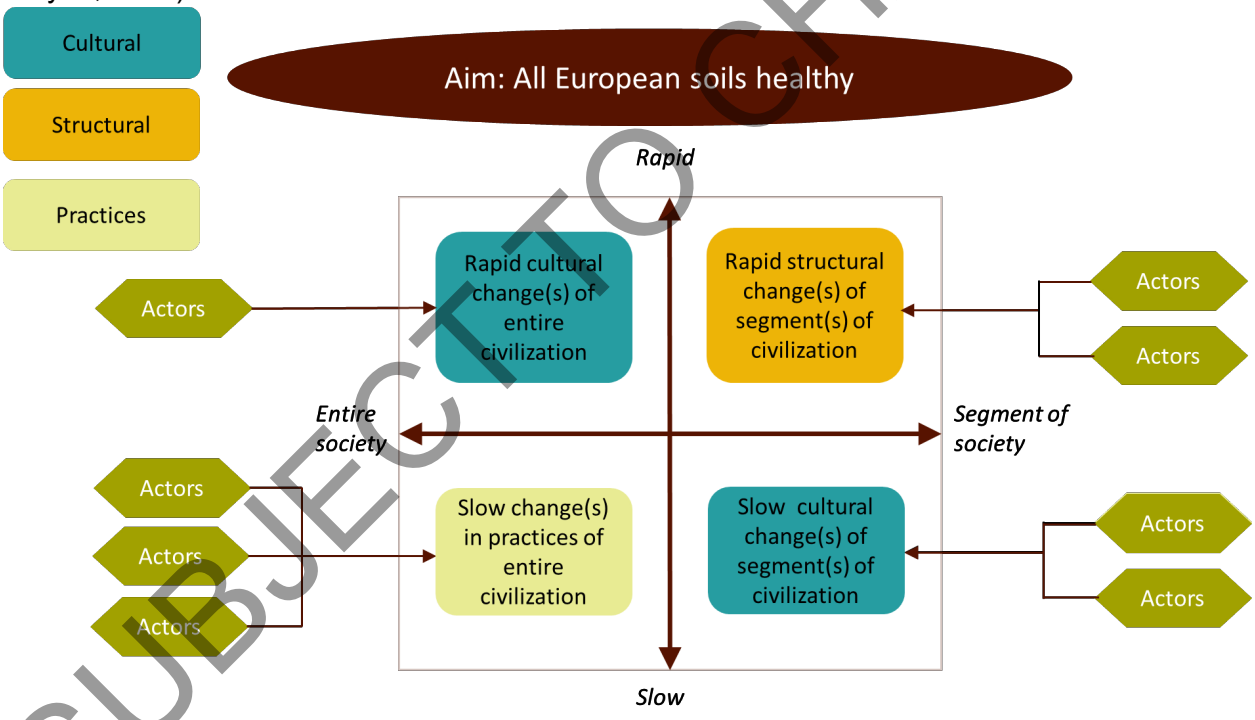

Figure 26. The conceptual framework illustrating the required societal changes across the different elements of society (i.e., cultural, structural and practices in blue, orange and yellow boxes, respectively) to increase the surface area of healthy soils from 30-40 to 100% in Europe by 2050. The x-axis demonstrates the scale at which these changes should take place: from the entire society to only particular societal segments. The y-axis demonstrates the rate at which these changes are expected to develop after taking action: rapid and potentially abrupt or slowly and gradually over time. The green boxes illustrate which societal actors are involved in implementing the postulated changes. Illustration adapted from (Linnér and Wibeck, 2020).

The basis of this framework consists of 2 vectors that depict the societal scale (x-axis) and rate (y-axis) of the required societal changes to achieve a 100% healthy soil status in Europe. The societal changes and key actors to implement these changes are indicated in the colored boxes.

The **scale** (x-axis) of the postulated changes represents whether the entire society (left-side of the figure), or only a particular societal segment (right-side of the figure) should be transformed. A particular societal segment can involve a supply chain, or a sector. The scale of the proposed changes does *not* apply to the differentiation between regional – national – European scale. Globalization and the strong European connection between countries resulted in societal systems that are tightly interconnected across nations. Transforming a specific societal segment will therefore often include changes at regional, national and European level.

The y-axis indicates at which **rate** the changes are expected to evolve after taking the required actions. Changes that occur before 2050 are considered as 'rapid.' Changes that are expected to develop more gradually over time and will continue to take place after the end of the Soil Strategy, are considered 'slow.' These slower changes can still strongly contribute to achieving the Soil Strategy. For instance, it may take more than 35 years before the entire EU society has changed in e.g. diet, but within 35 years the number of actors that have changed can be substantial enough to lead to alternative societal subsystems, e.g. increasing the area of organic farming to 25% in 2030 (Farm to Fork Strategy). *Vice versa*, rapid changes in a particular societal segments can form a leverage point for a wider transformation of the whole society on a longer term (Linnér and Wibeck, 2020).

The **color of the boxes** depicts which elements of a society especially need to be changed (i.e., culture, structures, practices). Targeting one element will also influence the others. For instance, the development of a high-precision laser-weeding technology that autonomously targets and eliminates weeds would eliminate the need for chemical input or manual labour to remove weeds). The development starts with a change in the structure of the system, with developing the infrastructure and market that enables the production and distribution of the technology. The implementation of this technology would change daily practices of the land manager, as previous manual, physical or chemical weeding would be replaced by laser-based weeding technology. If the novel technology would be implemented at a large enough scale, it could even change the culture by altering norms and values about the current widescale use of chemicals that protect crops but harm organisms.

The green boxes depict what **actors** are key for realising the proposed societal changes. Researchers will not be positioned as key actors, as they will not drive the changes on their own. However, researchers can play an important role by grounding the required innovations with new knowledge.

Finally, the conceptual framework is focused on the *desired* changes to improve European soil health, but we acknowledge that many external drivers can bring *other* changes in future European soil and land management that cannot be controlled for, such as changes in international trade and safety. Moreover, the pedoclimatic zone and local soil characteristics determine the soil functions and ecosystem services to be delivered, and in this way shape the local society. In the conceptual framework, geophysics are not considered as a transformative factor, as they change much more slowly than the Soil Strategy timescale.

5.3 Applying the conceptual framework in SOLO

The land use determines what kind of soil functions are needed, and what this means for soil health and society. Therefore, the required societal changes are specified separately for the four main land uses:

- **Agriculture**: soils that are managed with the main purpose of providing food, fibre and/or biobased fuel, including a vast diversity of systems ranging from agroforestry, extensive livestock farming to intensive arable farming.
- **Forest**: soils that are covered with forests that are managed with the main purpose of providing wood and woody elements.
- **Urban-industrial**: soils that are situated in urban and industrial areas, underneath (e.g. asphalt/tiles/bricks) or nearby (e.g. private gardens or city parks) buildings and other anthropogenic inorganic constructions.
- **Nature**: soils that are located in areas with the primary purpose of nature conservation and/or providing regulating or controlling ecosystem services, such a natural forests and meadows, wetlands, or peatlands.

Together with experts from WP1 and WP3 the necessary societal changes for each of the land uses have been drafted and placed in a conceptual figure. For agriculture, the key actors for the changes were also identified. Since the key actors need to change their decision-making to realize postulated changes, a literature analysis is being carried out to outline the factors that influence decision-making. These factors are tailored on farmers as key actors for improving soil health in agricultural soils. This exercise has been targeted to farmers and agricultural soils, because 1) they have received most research on soil health and its change mechanisms; 2) agriculture is the most dynamic land management where changes can be applied on a yearly and sometimes monthly basis; and 3) since agricultural land involves the largest proportion of land use in Europe.

The first results were presented to SOLO partners and Think Tank members during the SOLO meeting in Evora (October 2025), and to more experts to identify and further develop the proposed societal changes. Next steps consist in:

1) Writing a scientific publication of the conceptual framework, where the framework will picture what needs to change for an improved soil health in Europe. The framework will also provide direction when formulating research and innovation topics with societal impact.
2) Integrating the bottom-up thematic synthesis with the top-down conceptual framework. We plan to embed the Think Tank roadmaps in the framework in a workshop with Think Tank members. Plans to integrate the framework with the regional roadmaps are under construction.

6 Conclusions

In the present deliverable, the synergies and trade-offs of prioritized knowledge gaps have been identified across Mission-Objectives and across regions. Synergies have been identified when a single activity may help to solve multiple knowledge gaps across various Mission Objectives or regions. Trade-offs occur when addressing different knowledge gaps across Mission Objectives or regions require separate and independent actions or funding activities, as addressing one knowledge gap limits the ability to address a knowledge gap of another Mission Objective or region. The following four synergies were found across Mission Objectives:

1) At least 40 % of the knowledge gaps of each Think Tank roadmap was related to the 'Drivers soil health'. Hence, knowledge gaps of all mission-objectives can be solved in overarching research and innovation actions on the 'Drivers of soil health.'
2) Half of the knowledge gaps in each Think Tank roadmap were somehow related to 'Soil monitoring', and 'Policy and land use planning'. The required actions are relevant for most Mission Objectives, except for *Soil literacy* and *Soil biodiversity*. Therefore, many knowledge gaps appear to be -often secondarily- related to policy innovations.
3) Knowledge gaps about the 'Impact of soil health on society' were mentioned in all Think Tank roadmaps, though they never emerged as being dominant. Also here, overarching actions on this theme seem promising for solving knowledge gaps of all Mission Objectives.
4) All Think Tank roadmaps except *EU global footprint on soils* addressed knowledge gaps related to developing 'Sustainable land and soil management' strategies, with 30-80% of the knowledge gaps predominantly focusing on this theme.

The strongest trade-off was observed for solving knowledge gaps on *EU global footprint on soils* and *Soil literacy versus* the other Mission Objectives. *EU global footprint on soils* most often did not have any knowledge gaps assigned to one of the overarching knowledge gaps, and few knowledge gaps were common between *Soil literacy* and most other overarching main knowledge gaps (Table 7). Specific funding may therefore be required to solve knowledge gaps on *EU global footprint on soils* and *Soil literacy*.
Finally, we evidenced that for all Mission Objectives, *what* knowledge is developed or applied matters as much as *how* this is done: on average 90% of the knowledge gap descriptions of each Mission Objective also specified the approaches to conduct the suggested research and innovation.

All overarching bottlenecks were related to seven or more Mission Objectives, pointing to very few trade-offs in overcoming implementation bottlenecks for solving knowledge gaps of all Mission Objectives. Overcoming the lack of standardization and/or absence of a monitoring system and/or research methods was related to all overarching knowledge gaps, highlighting a clear leverage point for research and innovation actions. Moreover, over half of the knowledge gaps were assigned to the overarching theme 'Soil monitoring', which means that the development of a harmonized monitoring system and adequate research methods requires research to optimize efficiency and/or efficacy. Overcoming 'Resource limitations' beyond European funding also proofed to be essential when developing actions for solving each of the overarching knowledge gaps.

We **conclude** that research and innovation actions leading to enhanced **standardization of monitoring systems and/or research methods** can effectively solve most knowledge gaps

both within and across Mission Objectives. **Overcoming resource limitations beyond European funding** forms another leverage point, for instance via **improving soil education**, increasing the efficiency of the allocation of existing resources, and reducing institutional barriers.

There were five synergies found across regions. The synergies operated at different spatial scales, varying from the regional scale at which Regional Nodes operated (approximately 30 x 30 km size), to part of, or the entire country, where the Soil Weeks have been organized, and to macro-regions (countries within northern, southern, western and eastern Europe) based on the Soil Weeks events:

1) All overarching knowledge gaps across Mission Objectives were relevant in all macro-regions.
2) 'Sustainable land and soil management' was the most important gap across at all spatial scales (region, country, macro-region). This knowledge gap was also relevant for all Mission Objectives , except for the *EU global footprint.*
3) The importance of the 'Livelihood, soil stewardship and communication' knowledge gap varied across regions, but was in the top 4 at all scales, from region up to macro-region. This overarching knowledge gap was especially relevant for the Mission Objectives *Soil Literacy*, *Desertification and land degradation* and *Soil erosion*, but less so for the other Mission Objectives.
4) The 'Soil monitoring', and to a slightly lesser extent 'Policy and planning' knowledge gaps were relevant for all regions and macro-regions and for most countries, except for Germany and Sweden. This overarching knowledge gap was highly relevant for all Mission Objectives.
5) 'Drivers of soil health' was relevant for country and macro-region, as well as for all Mission Objectives. However, within regions, drives of soil health were of less interest.

Although no evident trade-offs were identified, the Northern macro-region was most different from other macro-regions. In the North, the 'Drivers of soil health' and the 'Impact of soil health on society' knowledge gaps were much more relevant in other macro-regions, and gaps on 'Policy and land use planning', and 'Livelihood, soil stewardship and communication' were less relevant to the North. We **conclude** that especially the following three overarching knowledge gaps have a high potential for **synergistic actions to solve knowledge gaps relevant for both all Mission Objectives *and* all regions** (region, country, macro-region):

1) Sustainable land use and soil management.
2) Soil monitoring.
3) Policy and land planning.

Based on the insights of this entire overarching roadmap, we **propose four strategies** to further enhance efficiency and avoid overlaps in **solving knowledge gaps of different Mission Objectives**:

1. <u>Combine multiple Mission Objectives into individual research or innovation projects</u>

Taking the eight Mission Objectives as a starting point for research and innovation actions may lead to considerable overlap. Instead, grouping the objectives of the Soil Mission into eight overarching themes may enhance synergism and efficiency in solving bottlenecks and knowledge gaps by Research and Innovation actions (Table 7). Such an integrated and thematic research and innovation approach may also help to discern relationships among Mission Objectives. For example, effects of climate change on soil health may be addressed well from a Soil Mission-wide

perspective, for instance via investigating the effect of mitigation and adaptation stategies against climate change-induced soil erosion on soil and aboveground biodiversity loss. A Soil Mission-wide approach may also help examining how soil health could be enhanced by land and soil management practices, novel political strategies, and the impact of soil health on society. Our analysis points at that all suggested overarching themes to integrate Mission Objectives are relevant for soil stakeholders in all EU macro-regions.

2. Consider the entire societal system when formulating research topics for transformative change

Soils are part of societal systems, and soil health improvement depends on how land is used for agriculture, forestry, urban-industrial, or nature conservation purposes. Improving soil health therefore does not only require knowledge on soils and soil health, but also understanding of the societal processes involved. Improving the sustainability of soil and land will often require changes in societal use of soils, as that influences soil health. Achieving the different soil Mission Objectives, therefore, requires consideration of the entire societal system that relates to soils. Research and innovation may strongly contribute to achieving the required transformations when delivering the required knowledge and innovations for the societal changes, while involving key actors in the process, as well as in implementing results.

3. Include indicators of all Mission Objectives into one soil monitoring framework.

Half of the knowledge gaps of all Mission Objectives were related to soil monitoring (Table 8). The most important bottleneck for solving each of the overarching knowledge gaps was considered the lack of standardization, or even complete absence, of a soil monitoring system and/or adequate research methods (Table 11, Figure 19). These results point to an urgent need for research to support the development of a harmonized, generally shared monitoring system, including indicators for all Mission Objectives. Working on these aspects is crucial to make the EU Soil Health Monitoring Framework effective for producing building blocks to improve soil health in Europe. One major gap identifies the lack of soil biodiversity indices in the existing set of soil health indicators. The effects of the European footprint on soils outside Europe constitute a second one. These two aspects of the Soil Mission need further attention.

4. Include the expected knowledge and innovation delivery of running projects in the agenda for soil research

The SOLO roadmaps are based on the current scientific knowledge and that of stakeholders and users. However, these roadmaps do not yet anticipate what knowledge is expected to be delivered by ongoing European and national research and innovation actions. While the SOLO roadmaps depict knowledge that is currently missing, by 2026, the future updated roadmap will probably pinpoint long-term research and innovation actions for the coming 35 years. Completed, ongoing, and future research and innovation actions will continuously deliver new knowledge to scientists and stakeholders. We therefore recommend an evaluation of knowledge gaps that may be solved by ongoing research projects, both in relation to specific Mission Objectives and overarching themes. This evaluation will avoid repetition and overlaps between current, still unpublished results and calls for future research. As research evolves, such evaluation may need to be repeated regularly.

7 Acknowledgements

This synthesis could not have been made without the invaluable help and efforts of all SOLO participants. In addition, there are numerous people from outside the SOLO consortium involved as members of the Think Tanks, participants of the Regional Nodes workshops, as well as the colleagues, volunteers, and the general audience involved in the Soil Weeks activities.

Special thanks go to the leaders of the Think Tanks for their indispensable and timely contributions that enabled the integration of the roadmaps, and for organizing Soil Week events that resulted in regional inputs essential for this deliverable. A very special thanks are for Cristina Yacoub Lopez, who has organized the setting-up and the initial stages of the Think Tank groups. We also thank Katharina Helming and Teresa Pinto-Correia for invaluable discussions on the theoretical framework that has been used for the present synthesis and Justine Lejoly for her contributions to discussions and supervision of the SOLO work at NIOO-KNAW, and Martin Kirstgen and Ariane Voglhuber-Slavinsky for their work on roadmap development. We also thank all Regional Node leaders for all discussions and openness that resulted in lively workshops of which the inputs were instrumental to this synthesis. A sincere thank you to Cathy Busson for her tremendous editorial efforts on this deliverable.

Finally, special words of thanks are for Carlos Guerra, coordinator of SOLO, who brings together the SOLO community with never-ending drive and energy.

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