Ref. Ares(2024)8080072 - 14/11/2024

AI4SoilHealth

Policy brief: priority areas and data needs for EU soil monitoring and information systems D2.1

Version 4.0
April 2024

Lead Author: Giovanna Giuffrè (ISINNOVA)

Contributors: Maurizia Castellari, Valentina Malcotti, Dominique Lepore, Olena Liakh (ISINNOVA); Grant Campbell, (University of Aberdeen); David A. Robinson (UK Centre for Ecology and Hydrology); Cordelia Hughes (Soil Association)

Reviewed by: Isabella Leong, Aarhus University

Action Number: 101086179

Action Acronym: AI4SoilHealth
Action title: Accelerating collection and use of soil health information using AI technology to support the Soil Deal for Europe and the EU Soil Observatory

HISTORY OF CHANGES		
Version	**Publication date**	**Changes**
1.0	19/04/2024	• First Draft
2.0	24/4/2024	• Quality review
3.0	29/04/2024	• Final Version
4.0	21/10/2024	• Revised Version
5.0	13/11/2024	• Revised version

Content

Introduction

A substantial leap at the political level is required to achieve the objective of healthy soils by 2050. Given this ambitious target looming ahead and considering how soil stands as the last ecosystem awaiting regulation at the European level, there is a pressing need for policy "leapfrogging". Rapid regulatory progress is required to establish a comprehensive and responsive framework that not only protects soil health but also ensures its remediation through consistent monitoring. Creating an effective soil monitoring framework is essential for understanding soil conditions and driving impactful actions and initiatives across economic, social, and environmental sectors.

In recent decades studies have provided detailed insights into the various threats affecting soil health, thereby enhancing the awareness among EU policymakers about the urgency of protecting soil comprehensively and consistently. This increased awareness is reflected in several soil-driven research and policy initiatives. Although the scientific and political landscape around soil is becoming increasingly competent, there are research gaps to be filled and soil monitoring needs to be addressed holistically.

Overcoming soil knowledge gaps and soil data voids is key to powering an informed soil policy leapfrogging operation set to advance sustainable soil management. Presently, the available data is fragmented across Member States and our understanding of certain soil dynamics remains limited. As such, it is imperative to ascertain (and agree upon) what kind of ground-level information should be pursued to enhance our comprehension of soil and promote responsible soil care and land stewardship.

Against this background, the present policy brief aims to investigate in which ways the AI4Soilhealth project can contribute to current and future knowledge and data needs for the efficient monitoring of soils and the elaboration of effective soil-friendly policies.

While this task was in progress, a 'disruptive' development in soil policy came along, requiring a finetuning of the approach. The Soil Monitoring and Resilience Directive (SML) presented by the EC in July 2023 was a game-changer for the drafting of this policy brief for two main reasons. On one hand, the SML tabled a comprehensive framework for soil monitoring, highlighting knowledge gaps that the project could help fill. On the other hand, it offered the chance for the project to consider the proposed text and evaluate the extent to which AI4SoilHealth can support and relate to the current proposal. The evolving regulatory landscape led to refining the planned activities to better align with ongoing policy discussions, thereby effectively enhancing the project's development.

As the core document for WP2 activities, this brief is structured as follows:

Section 1 presents two levels of EU soil governance and conservation actions involved in the direct and indirect protection of soil health. The **Inner Circle** offers an **analysis of recent soil health-centered initiatives** and their needs for soil data. The Mission Board Implementation Plan, the Soil Strategy at 2030, and the Soil Monitoring and Resilience Directive are examined to understand soil data needs, report on progress made, and identify challenges ahead for setting a soil monitoring framework at EU-level. To complement the soil-relevant policy mosaic, the **Bigger Picture** provides an **overview of soil-related policies** and other key legislations which indirectly influence soil care and land stewartship.

Section 2 goes to the heart of the **soil policy needs assessment** by providing an extensive analysis of interviews conducted by AI4SoilHealth with EU officials and representatives' stakeholders. The semi-structured consultation with stakeholders is aimed at identifying soil relevance for different policy areas and assessing soil data monitoring needs in support of improved policymaking, towards the set-up and implementation of a comprehensive and harmonic soil health monitoring framework. The original respondents selected were mainly EC officers as well as stakeholders active in the European arena and, the AI4SoilHeath team chose to extend the interviews to representatives from the potential data "users" domain, including experts from national research institutes, farmers and landowners, and members of the industry network. Between October 2023 and April 2024, a total of 29 stakeholders were interviewed (see Annex 1 for the interview protocol and Annex 2 for the list of institutions of the respondents). Interviews were conducted in a semi-structured manner with the aim of exploring what kind of policy and data information was perceived by the interviewees as most needed to enhance the relevance of soil in his/her work.

Section 3 builds on lessons from existing soil initiatives and insights from stakeholders to formulate **exploratory questions that can support knowledge transfer across policy, science, and society.** These points of investigation - enhanced by the engagement of soil data providers and soil data users - are explored using visual representations meant to empower AI4SoilHealth's delivery of relevant inputs for a soil monitoring framework and provide a segmented identification of AI4SoilHealth users' needs and expectations. As such, the section performs as the ideal 'conclusion' to the policy brief by offering perspectives that could be taken into account across the project - particularly within WP3's,WP5's and WP7's activities -and consolidated in *D2.4: Policy brief: innovative policies and economic incentives for soil* health expected by the end of the project.

1. Soil health initiatives at the EU level

The Inner Circle

Within soil's inner circle are strategic initiatives and proposal focusing directly on enhancing soil health. This subsection offers a detailed outline of the soil-dedicated EU Mission, the EU Soil Strategy in place, and the proposed framework contained in the recent Proposal for a Directive on Soil Monitoring and Resilience (SML).

1.1. The Mission "A Soil Deal for Europe"

In 2021, the EU introduced Missions, as part of Horizon Europe (HE), to increase the impact and relevance of European research and innovation in addressing some of the most pressing global challenges. Mission boards, consisting of top independent experts, were appointed to elaborate visions for the future and prioritise concrete goals in five areas, including "Soil health and food". Based on proposals that the Mission boards handed over to the EC, the soil-centred Mission was reframed as *A Soil Deal for Europe* and included in the 2021 EC Communication on EU Missions (EC 2021) defining a new and innovative way to achieve ambitious and inspiring goals in selected areas. Since then, the five Missions (ranging from fighting cancer to adapting to climate change, protecting oceans, making cities greener and healthier and ensuring soil health and food) went through a preparatory phase during which detailed implementation plans, including objectives, budgets and indicators, were developed. EU Missions succeeded in preparing three Horizon Europe Missions' work programmes to ensure a fast roll-out of their actions.

A Soil Deal for Europe's goal is to set up 100 Living Labs (LLs) and Lighthouses (LHs) as a means to promote sustainable land and soil management in urban and rural areas and achieve the EU's policy objective of having all soils healthy by 2050. The "Caring for soil is caring for life" (EC 2020) report outlines the Mission's 4 building blocks:

- an ambitious **cross-scale, inter- and trans-disciplinary R&I programme**;
- **co-creation and sharing** in (LLs) and (LHs) within and across farms and forest, landscape and urban settings;

- a robust **soil monitoring programme** by each MS equivalent to that for other natural resources (air, water, and biodiversity) using agreed methodologies and including selected indicators;
- training, education, communication and citizen engagement embedded into all activities.

As highlighted by the Mission's evaluation report (EC 2023), the potential for the Mission is "*to tie together fragmented frameworks, policies, networks, etc. that all cover a specific part of soil health without making connections between topics like experimenting, monitoring, changing incentives, and adapting regulations for soil management practices that affect different ecosystem services and soil health indicators*". In addition, the Mission is a pioneer in elaborating a common framework for evaluating 'soil health' as well as grounds for putting the soil health protection and restoration needs into practice.

Like a two-faced Janus, successful soil protection and remediation requires a harmonious blend of **European action** on setting goals, values, indicators, and **local experiments** to effectively grasp soil health protection, use and remediation whilst considering the specific local soil conditions and governance structures.

On the European level, the Mission's Implementation plan includes eight specific objectives that contribute to the achievement of existing EU policy targets, backed by evidence analysis baselines, one (or more) policy targets, and the provision of measurable indicators. Objectives and indicators are reported in the table below, as refined in the EEA report (EEA, 2022). Three milestones have been achieved in the advancement of the Mission block related to the development of a "robust EU monitoring program" :1) the approval of Horizon Europe (HE) calls on soil health indicators' development and validation; 2) the agreement with the JRC to oversee Mission activities on the monitoring of soil; and 3) the launch of the EU Soil Observatory (EUSO) Dashboard. On top of this, the Soil Monitoring and Resilience Directive proposal (SML) is of paramount importance for the establishment of a robust set of definitions, indicators, reference values, and monitoring practices to be complemented by policy designs/adaptations that demand and reward soil health improvements.

On the local level, the Mission's focus on LLs and LHs is the way forward to ensure variability in how actors like farmers, foresters, landowners, public authorities, and citizens will experiment, interact with, and learn about soil health practices. Grounding knowledge-building on the place-specific variations in soils, soil usage, and institutional landscapes characterizing regions across Europe improves the land stakeholders' receptiveness of and compliance to soil-friendly practices and increases the chances of success for an integrated EU monitoring system.

In an effort to harmonize actions and different territorial and legislative levels, the Mission's present, and future calls aim to fund initiatives mobilising and connecting communities working on soil protection (researchers, land managers, policymakers, industries, etc.). Although operating at different levels of the soil health value chain, the challenge to which all Mission-funded projects are called to contribute is ensuring complementarity and synergies among soil stakeholders' efforts across the EU, national and local levels.

Table 1 Objectives, targets, and recommended indicators of the EU's Mission Board for Soil Health and Food – in green the main areas of working for AI4SoilHealth (D3.1)

Mission Objectives	Mission targets	Precence of pollutants	Soil organic carbon stock	Soil structure bulk density & absence of soil sealing /erosion	Soil biodiversity	Soil nutrients and pH	Vegetation cover	Landscape heterogeneity	Area of forest and other wodedlands
1. Reduce land degradation related to desertification	T 1.1: 50% of degradaded land is restored to help achieve land degradation neutrality and start restoration.	✓	✓	✓	✓	✓	✓	✓	✓
2. Conserve and increase soil organic carbon stocks	T 2.1: Current carbon concentration losses on cultivated land (0.5% per year) are reversed to an increase by 0.1-0.4% per year.		✓				✓		
	T 2.2: the area of peatlands and wetlands losing carbon is reduced by 30-50%.		✓				✓		
3. No net soil sealing and increase the reuse of urban soils	T 3.1: switch from 2.4% to no net soil sealing.			✓			✓		
	T 3.2: the current rate of soil re-use is increased from 13% to 50%.			✓			✓		
4. Reduce soil pollution and enhance restoration	T 4.1: 25% of land under organic agriculture.	✓							
	T.4.2: a further 5-25% additional land (over and above the 25% in full organic) with reduced risk from euthophication, anti-microbials and contaminats.	✓							
	T.4.2: doubling the rate of restoration of contaminated sites.	✓							

5. Prevent erosion	T 5.1: stop erosion on 30%-50% of land with unsustainable erosion risks.			✓					
6. Improve soil structure to enhance habitat quality for soil biota and crops	T 6.1: reduce by 30%-50% soils with high density subsoils.			✓			✓	✓	
7. Reduce the EU global footprint on soils	T 7.1: the impact of EU's food, timber, and biomass imports on land degradation is reduced by 20-40%.								
8. Increase soil literacy in society across Member States	T. 8.1: Soil health is firmly embedded in schools and educational curricula.	✓	✓	✓	✓	✓	✓	✓	✓
	T.8.2: uptake of soil health training by land managers is increased.	✓	✓	✓	✓	✓	✓	✓	✓
	T 8.3: understading of impact of consumer choices on soil health is increased.	✓	✓	✓	✓	✓	✓	✓	✓

1.2. The EU Soil Strategy for 2030

EC Communications are documents issued by the European Commission to evaluate policies, clarify current strategies, and provide useful frameworks to interpret policies. Although EC Communications are not legally binding, these play a significant role in shaping future policies. In line with this, as part of the EU Soil Strategy for 2030 (EC 2021c), the EC has proposed a vision and laid down objectives for the *protection, restoration, and sustainable use of soil*, in alignment with the European Green Deal's aspirations for 2050, where all soil ecosystems are expected to be in a healthy condition by 2050, contributing to i) climate neutrality and resilience to climate change; ii) a clean and circular economy; iii) halting desertification, and reversing land degradation.

As detailed in Section 1.4, the EU Soil Strategy recognizes soil health as a cornerstone to reach the targets set by the Green Deal's subsequent strategies and actions. However, it also highlights how current soil protection existing at the EU level is a by-product of parallel initiatives focused on other environmental issues, goals, and targets (EC, SWD 2021). This 'indirect' protection of soil is somehow reflected in the monitoring framework contained in the SML, where selected soil descriptors are all connected with different policies subject to a wide range of governance systems. Furthermore, the EC has committed to advancing soil health through various Union-led programs, including – among others - the Common Agricultural Policy, the Cohesion Policy funds, and the Programme for Environment and Climate Action. These programs will provide objectives that contribute to healthy soils, supported by financial and technical assistance mechanisms.

One of the key features of the Soil Strategy is a proposed list of policy measures and actions to be adopted by 2030 – including the development of a Soil Health Law by 2023. Data wise, the Strategy stresses the potential for open data standards to improve the interoperability of national, EU, and global soil monitoring frameworks (EU, 2007). The Strategy identifies LUCAS as the central soil initiative offering harmonized EU-wide measurements and proposes its further integration and expansion. Among the enabling measures listed by the Strategy related to soil and the digital agenda, soil data and monitoring, as well as soil R&I, the following are particularly relevant:

- enhance the use of digital tools and Copernicus and rely on the JRC to further develop the European Soil Observatory (EUSO) and on the EEA to develop the Land Information System for Europe (LISE), supported by geospatial analytical products;
- improve the modelling capacity of soil-related processes under Destination Earth, in collaboration with the Horizon Europe Mission;
- develop an integrated soil indicator system to serve as an umbrella for further monitoring and reporting, with the combination of data flows coming from MS, JRC, EEA, and other sources (EEA, 2021). While building on existing national and EU schemes to gain a better understanding of diffuse soil contamination, special attention should go to: considering the provisions on monitoring soil biota to account for soil biodiversity; setting - through the LUCAS soil surveys – an EU-wide harmonised monitoring system to track evolutions in soil organic carbon content and carbon stocks; and integrating a pollution module in the future LUCAS 2022 soil survey.
- when implementing the EUSO, it is important to identify soil monitoring gaps with the help of the European joint programme on agricultural soil management, through discussions with Member States and other key stakeholders. Develop a soil dashboard with a set of reliable soil indicators, integrating trends and foresight.
- encourage and support Member States in setting up farm sustainability tools for nutrients (FaST), as part of the farm advisory services under the new CAP. Such tools will provide farmers with recommendations on the use of fertilisers, compliant with existing legislation and based on available data and knowledge.

1.3. Proposal for a Directive on Soil Monitoring and Resilience

The recently proposed Directive on Soil Monitoring and Resilience (SML) which has brought AI4SoilHealth to adopt a new angle to its science-policy discourse aims to set a flexible, proportionate framework for monitoring and assessing soil to improve its protection, support its remediation, and achieve healthy soils by 2050. The SML builds on specific soil targets while also promoting the achievement of objectives related to mitigating climate change, protecting nature, eliminating pollution, and ensuring the sustainability of the food system. Although amendments to the proposal have already been submitted and are currently under discussion, among the main issues addressed by the original proposal are:

Soil health monitoring and assessment begins with a clear definition of soil health, the creation of Soil Districts and a list of Soil Descriptors to be monitored though established data points - The proposal puts forward a common definition of what constitutes soil health[1] and land take[2] and lists principles for soil sustainable management (SSM). To comply with the Directive, Member States would be required to establish 'soil districts' – which should correspond at least to the number of NUTS 1 at territorial level – and appoint one competent authority for each. In setting the districts, Member States may take into account existing administrative units and shall seek homogeneity within each soil district regarding the following parameters: soil type, climatic conditions; environmental zone, land use or land cover as used LUCAS programme.

Member States would have the obligation to monitor soil health and land take in each soil district implementing all required actions to ensure monitoring and measurements. In Annex I, the SML contains a proposed list of **12 soil descriptors**, associated with criteria or range of criteria and the corresponding methodologies and/or transfer function, to be adopted by MS. Soil descriptors are divided in three categories: a) descriptors with criteria for healthy soil conditions established at EU level b) descriptors with criteria set at MS level and iii) descriptors without criteria. Following interaction with the EC, MS would be able to adapt some of the EU descriptors and criteria to fit specific local conditions and/or add additional descriptors.

---

[1] "'soil health' as 'the physical, chemical and biological condition of the soil determining its capacity to function as a vital living system and to provide ecosystem service" (art.3.4).

[2] Land take is defined as "means the conversion of natural and semi-natural land into artificial land"

Table 2 Soil aspects and soil descriptors listed in Annex 1 SML – highlighted in green the main areas of work for AI4Soilhealth (D3.1)

Aspect of soil degradation	**Soil descriptor**
PART A – soil descriptors with criteria for healthy soil condition established at Union level	
Salinization	Electrical conductivity (deci-Siemens per meter)
Soil Erosion	Soil erosion rate (tonnes per hectare per year)
Loss of organic carbon	Soil organic carbon (SOC) concentration (g per kg)
Subsoil compaction	Bulk density in subsoil (upper part of B or E horizon);
PART B – Soil descriptors with criteria for healthy soil condition established at Member States level	
Excess nutrient content in soil	Extractable phosphorus (mg per kg)
Soil contamination	Concentration of heavy metals in soil: As, Sb, Cd, Co, Cr (total), Cr (VI), Cu, Hg, Pb, Ni, Tl, V, Zn (µg per kg)
Reduction of soil capacity to retain water	Soil water holding capacity of the soil sample (% of volume of water / volume of saturated soil)
Part C: Soil descriptors without criteria	
Excess nutrient content in soil	Nitrogen in soil (mg g -1)
Acidification	Soil acidity (pH)
Topsoil compaction	Bulk density in topsoil (A-horizon4) (g cm-3)
Loss of soil biodiversity	Soil basal respiration ((mm3 O2 g -1 hr-1)
Part D: land take and soil sealing indicators	
Land take and soil sealing indicators	Total artificial land (km² and % of Member State surface) Land take, Reverse land take Net land take (average per year–- in km² and % of Member State surface) Soil sealing (total km² and % of Member State surface)

Member States are required to monitor and assess soil conditions to obtain a sufficient number of data points, taking into account the variability of soil conditions. According to simulations by the European Commission (EC), this would demand an assessment of approximately 5% of EU soil, representing a threefold increase compared to current LUCAS and Member States' data points. The EC will support monitoring efforts through the LUCAS program, enhancing remote sensing products utilizing data from Copernicus, and developing the EUSO portal.

Upon the Directive's coming into force, Member States are required to complete the first soil monitoring within four years and the initial assessment within every five years. An early evaluation of the Directive is planned six years after its enforcement to assess the need for adjustments or revisions based on the data collected. While there is no standardization, While there is no methodological harmonization across Member States is recommended. The SML's Annex I includes a requirement to adopt a 'validated transfer methodology' consistent with the reference methodologies provided.

Applying a "one out, all out" approach to the soil descriptors' values compliance would label as healthy soils uniquely those meeting the associated criteria established at the EU and Member State level for all soil descriptors values. Soil descriptors without criteria, as well as land take and soil dealing indicators, will not be part of the soil health assessment.

Member States also have the obligation to set up a voluntary soil health certification process. This allows to use data collected from soil monitoring to support and reward soil managers. MS could also explore the creation of synergies between this soil health certification and the carbon removal one.

Sustainable soil management practices must be consistent with measures present in other environmental legislations and made accessible to land stakeholders, including the provision of awareness-raising and training -Annex III of the Soil Management Law establishes fundamental principles for sustainable soil management, drawing inspiration from the Common Agricultural Policy (CAP) Good Agricultural and Environmental Conditions (GAECs) but applicable to all types of soil. It delegates the responsibility of defining positive soil management practices to Member States (MS), taking into consideration the soil type, usage, and condition. These practices are to be gradually implemented on soils identified as unhealthy.

Member States are required to ensure that sustainable soil management and regeneration practices are consistent across relevant plans, programs, targets, and measures mandated by other EU legislation, as listed in Annex IV. These include:

- Nature restoration plans under the Nature Restoration Regulation,
- CAP strategic plans,
- Action programs under the Nitrates Directive,
- River basin management plans under the Water Framework Directive,
- National air pollution control programs under the NEC Directive,
- Integrated national energy and climate plans under the Regulation on the Governance of the Energy Union and Climate Action.

Member States must also ensure the engagement of relevant stakeholders in identifying and defining sustainable practices, as well as providing access to independent advice, training, and funding opportunities for land managers, landowners, and relevant authorities.

Risks assessments and management of contaminated sites - By the Directive's fourth year of enforcement, Member States are required to establish a register of contaminated and potentially contaminated sites. Within seven years, these sites must undergo soil investigations to determine the presence of contamination. Each country has the autonomy to determine the deadline, content, format, and prioritization of these investigations.

For each site, Member States must conduct a site-specific risk assessment to evaluate whether the contamination poses unacceptable risks to human health. Based on the assessment, appropriate risk reduction measures must be implemented

What next? The Legislative process and the amendments under discussion – The course of legislation foreseen for the SML is one subject to ordinary legislative procedure with the joint adoption by the European Parliament and the Council of the European Union. In the European Parliament, the Committee on Environment, Public Health, and Food Safety (ENVI) is responsible for the file while the Committee on Agriculture and Rural Development (AGRI) is expected to give an opinion.

On 11 March, 2024 ENVI adopted its report – containing key amendments to the SML that will be discussed by the European Parliament in April 2024 - leaving the file 'open for discussion' for the next European Parliament appointment. Among the main points reviewed are: :

- Conversion of the EU's goal of healthy soils by 2050 from a visionary to a compulsory target, suggesting the Commission should contemplate interim 2040 targets in the Directive's first six-year review.
- Mandate for MS to collaborate among bordering soil districts that share comparable values for the parameters. Where relevant, these districts should engage in the exchange of best practices and work together to guarantee the adoption of a uniform approach across national boundaries.
- Mandate to the EC to establish working groups aiding MS in the implementation process by providing capacity building and consulting, following the steps of the Soil BON initiative.
- Mandate the EC to create a free, sustainable soil management toolbox for soil managers, including best practices and information on their effects on ecosystem services.Proposal for

a novel soil health assessment method with a five-tier soil ecological status classification (high, good, moderate, degraded and critically degraded) where healthy soils are those with high or good status. Member States would have a decade to improve critically degraded soils, and six years for those of moderate or degraded status. Localized soil district plans would be developed, catering to specific regional needs, with clear targets to enhance soil health.

- Introduction of a tiered approach for soil monitoring, enabling Member States to select a tier that best suits their specific requirements, provided they meet at least the basic conditions outlined in Tier 1 which, based on the Commission's initial proposal, incorporates additional criteria such as descriptors for soil contamination (including pesticides, biocides, and PFAS), as well as ecological functions, biodiversity, and habitat (see Table 3). Threshold values for soil descriptors would be established at the EU level for the first two tiers, with Member States able to adjust these values by up to 20% for Tier 2.

Table 3 Soil aspects and soil descriptors proposed by EP for Tier 1 soil monitoring design - highlighted in green the main areas of work for AI4Soilhealth (D3.1)

Degradation factor	**Soil descriptor**
Soil Erosion	Soil erosion rate (tonnes of loss soil per hectare per year (t $ha^{-1} yr^{-1}$))
Loss of organic carbon	Soil Organic Carbon (SOC) concentration (g of Carbon per kg (g kg^{-1}))
Subsoil compaction	Bulk density in topsoil (g cm^{-3})
Excess nutrient content in soil	• Available phosphorus (mg kg^{-1}) • Total Nitrogen in soil (mg g^{-1})
Soil contamination	• Concentration of heavy metals in soil: As, Sb, Cd, Co, Cr (total), Cr (VI), Cu, Hg, Pb, Ni, Tl, V, Zn (µg per kg) • Concentration of a selection of organic contaminants established by Member States and taking into account contaminants covered by Regulation (EU) No 2019/1021 and existing concentration limits e.g. for water quality and air emissions in Union legislation especially priority substances under the Water Framework Directive and related Environmental Quality Standards (Directive 2008/105/EC) and the Groundwater (Directive 2006/118/EC) Directives • Plant protection product candidates for substitution and substances authorised under emergency regime, and biocides residues • Per- and poly-fluorinated alkyl substances (PFAS) total or sum of PFAS total
Reduction of water retention	• Soil water holding capacity of the soil sample (% of volume of water) • Volume of saturated soil
Acidification	Soil acidity (pH H2O)
Salinization	Electrical conductivity (deci-Siemens per meter)
Soil ecological functions	**Soil descriptor**
Soil aggregation	water-stable aggregates (%)
Soil respiration	Soil microbial basal respiration (µl O_2 h^{-1} g^{-1} soil dry weight)

Soil biomass	Soil microbial biomass carbon (Cmic µg C g^{-1} soil dry weight)
Soil biodiversity	**Soil descriptor**
Taxonomic diversity	Diversity of soil organisms through (presence counts per taxonomic group) based on metabarcoding targeting the 16S and 18S rRNA gene regions and using the Internal transcribed spacer region (ITS) in particular for Fungi (additionally, other markers like COI for soil fauna can be considered)
Population abundance	• Total abundances of bacteria and archaea (using 16S rRNA gene region copies) • Total abundances of fungi (using 18S rRNA gene region copies) • Total number and proportion of pathogenic fungi • Total nematode abundance per functional group based on morphology (bacterial feeders, fungal feeders, root feeders, omnivores, predators)
Soil habitat	
Soil structure	• Size class proportions (sand, silt, clay) • Proportion of coarse materials (>2mm)

The Bigger Picture

Due to its multifunctional role in environmental sustainability, economic resilience, and societal well-being, healthy soils play a key role in achieving the EU's ambitious environmental and climate objectives. As such, in addition to the recent soil-specific initiatives discussed in the previous sections, soil has a place in a broad web of directives and regulations aiming to secure wider environmental conservation and sustainability. The following sub-sections (1.4. and 1.5) describe the policy objectives and targets in which soil health plays a role and provides an overview of six main EU legislations (approved or under discussion) - as identified by the SML Impact Assessment - in the context of climate, biodiversity, and agricultural policies that contemplate soil health as a vital component for the success of a wider ecosystems' protection. Other Directives, and their relevance for soil, are also mentioned.

1.4. Framing soil health-relevant objectives in EU strategies & legislations

To effectively contextualize the EU's overall ambition for soil, it is important to place it within the broader framework of the Green Deal and the 'Twin' transition (green and digital). The EC adopted the landmark communication *European Green Deal* in 2019 (EC, 2019) as a blueprint for transformational change. It was then refined in 2021 through the *Fit for 55* package (EC, 2021c), hosting a series of strategies, from forest management to pollution abatement. The objectives announced in these 'soft law' acts are not binding and need to be embedded into binding secondary legislation to influence tangible progress towards these goals.

The transformation of these strategies, of which soil protection and remediation is a part, is dependent on a complex normative process where “directives and regulations intertwine in a flurry of public policies, subject to variable competences (exclusive, shared, etc.), and involving institutions with divergent, if not antagonistic, interests” (de Sadeleer, 2023).

These strategic communications relate to policy areas that are often either fragmented or partially harmonized – thus, the challenge is the adoption by the European Parliament and the Council of the legislative proposals derived from the strategies proposed. Considering the current political climate and the nature of the legislative change required, this endorsement process should not be taken for granted or underestimated. The recent withdrawal of the Sustainable Use of Pesticides Regulation (SUR) (EC, 2022), an initiative promoted under the European Union's Farm to Fork strategy designed to enhance the environmental sustainability of food systems, serves as a warning.

At the same time, it is also a matter of developmental stages: soil policy is still in its ‘infancy’, as its protection measures need to be integrated and rely on the successful approval and implementation of other environmental and agricultural policies (Heuser, 2022**). Ensuring policy coherence across current legal initiatives across sectors is as crucial as enacting new soil-specific legislation**.

For research projects such as AI4SoilHealth, this ‘open to work’ scenario may serve as a drive to actively involve societal actors in project activities and to disseminate project results widely, thereby increasing awareness of soil’s role across different economic and societal fields.

Table 3 summarizes the soil-related policy objectives and targets outlined in several EU Strategies as well as the most relevant legislations derived from them (approved or under discussion). The table includes references to objectives mentioned during the stakeholders’ interviews conducted to support the elaboration of this brief (Q1). Colour coding differentiates between soft legislation (not biding – green) and hard legislation (binding – red)

Table 4 - Soil-related policy objectives and targets in the Green Deal Strategies and relevant subsequent legislative acts and proposals highlighted in green the policy references for AI4Soilhealth (D3.1).

EU Strategies & Legislations	Policy Objectives & Targets
EU Soil Strategy for 2030 (EC, 2021e)	✓ All EU soil ecosystems are in a healthy condition and, thus, more resilient by 2050.

	✓ Combat desertification and achieve no net land take; to restore degraded ecosystems, including soils. ✓ Contribute to (1) land-based climate neutrality by 2035, and (2) reducing the impact of soil pollution (on ecosystems, waters, and human health).) ✓ Achieve progress in the management of contaminated sites
EU Climate Adaptation Strategy (EC, 2021)	✓ Achieve a climate-resilient society for Europe, fully adapted to the unavoidable impacts of climate change by 2050.
Communication for Sustainable Carbon Cycles (EC, 2021)	✓ Provide every land manager with access to verified emission and removal data by 2028 to enable a wide uptake of carbon farming. ✓ Set that carbon farming initiatives should contribute to the increase by 42 Mt CO2eq of the land sink that is required to meet the objective of 310 Mt CO2eq net removals by 2030.
Climate Law Regulation (EU, 2021/1119)	✓ Set a legally binding target of net zero greenhouse gas emissions by 2050, and at least a 55% reduction by 2030 (as compared to 1990).. Recognise the need to enhance the EU's carbon sink through a more ambitious LULUCF regulation.
Land Use Land Use Change and Forestry Regulation (EU) 2023/839) (EU, 2018/841)	✓ Sets the EU target of making the LULUCF sector a net carbon sink, removing 310 Mt of CO_2 by 2030. ✓ Binding commitments for MS to compensate CO_2 emissions from the land use sector andabide to land management practices that increase soil organic carbon stocks .
Regulation for establishing a Union certification framework for carbon removals (Proposal- EC, 2022)	✓ Accelerate the deployment of verifiable, high-quality carbon removals ✓ Ensure the EU's capacity to quantify, monitor, and verify carbon removals.
A new Circular Economy Action Plan for a cleaner and more competitive Europe (EC, 2020)	✓ Promote initiatives to reduce soil sealing, rehabilitate abandoned or contaminated brownfields, and increase the safe, sustainable, and circular use of excavated soils.
Biodiversity Strategy for 2030 (EC, 2020e)	✓ Legally protect a minimum of 30% of the EU's land area. ✓ Sets the targets of at least 25% of the EU's agricultural land under organic farming and a significant increase in organic aquaculture by 2030. ✓ Recommends at least 10% of the agricultural area is under high-diversity landscape features. ✓ Reduce therisk and use of chemical pesticides by 50%, and the use of more hazardous pesticides by 50%.
Farm to Fork strategy (EC, 2020f)	✓ To reduce the overall use and risk of chemical pesticides by 50% and the use of more hazardous pesticides by 50% by 2030 ✓ Reduce the use of fertilisers by 2030 by at least 20%. ✓ Establishes that at least 25% of the EU's agricultural land is under organic farming and a significant increase in organic aquaculture by 2030.

Zero pollution action plan for air, soil, and water (EC, 2021c)	✓ A zero pollution ambition for a toxin-free environment for air, water and soil. ✓ Improve monitoring, reporting, prevention and remedy pollution from air, water, soil, and consumer products to levels that are no longer harmful to human health and to the environment. ✓ Propose a new legislation covering significant pollution sources, that are not yet addressed by other policies, strategies, and protocols. ✓ Facilitate remediation of soil pollution via (1) a monitoring framework on the state of pollution and (2) an outlook report, including a specific assessment of the evolution of human health and environmental impacts.
Action plan for the development of organic production (EC, 2021)	✓ The action plan is broken into three interlinked axes that reflect the structure of the food supply chain and the Green Deal's sustainability objectives: Axis 1: stimulate demand for organic products by increasing the awareness of its benefits and ensuring consumer trust in the organic logo. Axis 2: stimulate conversion and reinforce the entire value chain. Axis 3: organics leading by example: improve the contribution of organic farming to environmental sustainability.
EU forest strategy for 2030 (EC 2021b)	✓ Improve the quantity and quality of EU forests, reversing negative trends and adapting EU forests to the new conditions, weather extremes and high uncertainty brought about by climate change. ✓ Includes a set of regulatory, financial, and voluntary measures for 2021-2030, among which: promoting sustainable forest management (SFM), providing financial incentives for forest owners and managers to adopt environmentally friendly practices, and improving the size and biodiversity of forests, also through planting 3 billion new trees by 2030.
Nature Restoration Regulation (EC, 2022)	✓ Set the target to restore at least 20% of the EU's land and sea areas by 2030 and all ecosystems in need of restoration by 2050. To reach the overall EU targets, MS must restore at least 30% of habitats covered by the new law from a poor to a good condition by 2030, increasing to 60% by 2040, and 90% by 2050. EU countries should give priority to Natura 2000 areas until 2030. Once in good condition, EU countries shall ensure an area does not significantly deteriorate. ✓ Improve biodiversity in agricultural ecosystems, by making progress in two of the following three indicators: a) the grassland butterfly index; b) the share of agricultural land with high-diversity landscape features; c) the stock of organic carbon in cropland mineral soil. Measures to increase the common farmland bird index must also be taken as birds are good indicators of the overall state of biodiversity. ✓ Introduce a limit value for drainage of wetlands and organic soils and set targets to restore managed and drained peatlands. Specifically for organic soils in agricultural use constituting drained peatlands, MS shall put in place restoration measures. Those measures shall be in place on at least: (a) 30 % of such areas by 2030, of which at least a quarter shall be rewetted; (b) 50 % of such areas by 2040, of which at least half shall

	be rewetted; (c) 70 % of such areas by 2050, of which at least half shall be rewetted. ✓ Demands a positive trend in several indicators of forest ecosystems and an additional three billion trees to be planted. ✓ Requests MS to restore at least 25,000 km of rivers into free-flowing rivers and ensure there is no net loss in the total national area of urban green space and of urban tree canopy cover.
Regulation (EU) 2023/1115 on deforestation-free products	✓ Avoid that the listed products Europeans buy, use, and consume contribute to deforestation and forest degradation in the EU and globally. ✓ Reduce carbon emissions caused by EU consumption and production of relevant commodities by at least 32 million metric tonnes a year. ✓ Address all deforestation driven by agricultural expansion to produce the commodities in the scope of the regulation, as well as forest degradation.

1.5. Framing soil health-relevant legislations

Along with aspects addressed in soil-specific legislation proposals discussed in 1.1., 1.2. and 1.3., the protection and remediation of EU soils is partially covered by several interconnected legislations – some of which are under discussion or have been recently approved in the context of climate, biodiversity, and agricultural policies. The SML Impact Assessment Report (EC, 2023), contains a baseline policy scenario collecting some of the most relevant legislations expected to be enacted alongside the SML, covering specific characteristics of soils. Six of these policy initiatives were repeatedly mentioned during the stakeholder interviews (Q2 and Q4) offering insights into the opportunities, challenges, and risks tied to their enforcement.

Table 5 – Six recent soil-relevant policy legislations (approved and/or under discussion) derived from the SML's Impact Assessment information (Annex I)

	Prevention of pollution	Pollution remediation	Soil Carbon - organic soil	Soil carbon - mineral soil	Soil sealing	Erosion	Compaction	Soil biodiversity	Excess of nutrients /nutrients loss	Salinisation	Acidification	Water retention
Nature Restoration Law Regulation (Proposal EC, 2022)												

LULUCF amending Regulation (EU 2023/839)												
Carbon Removal and Carbon Farming Regulation (CRCF) (EU 2022/0394)												
Common Agricultural Policy - National Strategic Plans												
Proposal for a directive amending Industrial Emissions Directive 2010/75/EU (Proposal EC, 2022)												
Integrated Nutrient Management Action Plan (INMAP) (Proposal, EC 2022)												

The Nature Restoration Law Regulation (NRR) sets EU targets and procedures for restoring degraded ecosystems, with some measures directly relevant to soil, as highlighted in Table 3. Adopted in March 2024,the NRR mandates Member States to develop national plans with binding targets for restoring degraded ecosystems, especially those with the greatest potential for carbon capture and storage, and for mitigating natural disasters. The approach includes setting initial targets for ecosystems with existing data and monitoring frameworks, specifically habitats listed in Annex I of the Habitats Directive and those covered by the Birds Directive. For ecosystems with insufficient data and monitoring, Member States must ensure a positive trend in key biodiversity indicators. Simultaneously, a process will be established for developing an EU-wide methodology to assess the condition of these ecosystems.

The **revision of Regulation (EU 2018/841 - (LULUCF Regulation)**, approved in April 2023. This revision aims to promote nature-based solutions for mitigating GHG emissions and reducing the impact of land management and forestry practices on climate change (Böttcher et al, 2019). Under the regulation, Member States must account for their GHG emissions and removals from natural and managed land in five-year cycles and adhere to the 'no-debit rule', requiring them to offset any extra emissions from land use, land use change, or forestry practices with additional CO_2 sequestration. However, the complexity lies in using modeling to establish baseline rates of GHG emissions/sinks for each land category in each state. The LULUCF revision sets a Union-wide target of making the LULUCF sector a net carbon sink, removing 310 Mt of CO_2 by 2030 from 2026. The Commission will determine each Member State's contribution to this target in a delegated regulation after 2024. The revision leverages technological developments for accurately measuring GHG emissions from land. Starting from 2026, Member States will report their actual GHG emissions and removals from LULUCF based directly on remote (satellite) and in-field data.

The proposed **Carbon Removal and Carbon Farming Regulation** (CRCF) (EU 2022/0394) aims to facilitate the deployment of high-quality carbon removals through a voluntary Union certification framework. The European Parliament reached an agreement on the proposal in March 2024. This proposal defines criteria for high-quality carbon removals and outlines the process to monitor, report, and verify their authenticity. The framework outlines four types of carbon removals, two of which are most relevant for soil health: a) Temporary carbon storage from carbon farming, such as restoring forests and soil, wetland management, and seagrass meadows (minimum five years) b) Soil emission reduction obtained from carbon farming, such as wetland management, no-till, and cover crop practices (minimum five years).

The **'new' Common Agricultural Policy (CAP)** for the period 2023-2027 is structured around ten key strategic objectives, one of which is specifically aimed at preserving natural resources, including soil (SO 5 – Foster sustainable development and efficient management of natural resources such as water, soil, and air, including by reducing chemical dependency). Under the CAP's first pillar, payments are contingent upon compliance with a set of statutory management requirements (SMRs) and good agricultural and environmental conditions (GAECs). GAECs particularly relevant to soil protection and quality include:

- GAEC5: Tillage management to reduce the risk of soil degradation and erosion, with consideration given to slope gradient.
- GAEC6: Maintaining minimum soil cover to prevent bare soil during sensitive periods.
- GAEC7: Implementing crop rotation on arable land, excluding crops grown underwater.

In the CAP's second pillar, Member States implement Agri-Environment-Climate Measures (AECMs), which focus on supporting farmers in climate change mitigation. Examples of these measures include:

- Supporting organic farming to preserve soil health and biodiversity.
- Implementing forestry development measures effective against soil erosion.
- Investing in machinery for conservation tillage to minimize soil disturbance and maintain soil cover, potentially reducing greenhouse gas emissions, erosion, and enhancing soil organic matter.

The final design of CAP interventions varies depending on Member States' scenarios and priorities, resulting in a wide range of contributions to soil health (EC, 2023).

The **Industrial Emissions Directive** (IED) is the primary EU instrument regulating pollutant emissions from industry. It applies to large agro-industrial installations undertaking activities listed in Annex I of the IED - covering around 52,000 installations of which more than half operating in the farming and waste sectors (EP, 2023). Permits issued by national authorities must consider the overall environmental performance of the plant, including emissions to air, water, and land, waste generation, raw material use, energy efficiency, noise, accident prevention, and site restoration upon closure. Permit conditions must be based on the Best Available Techniques (BAT), which are determined at the EU level through the development of 'best available techniques reference documents' (BREFs) for each sector. The proposal for a revision, tabled in April 2022, seeks to bring it into line with the EU's zero pollution ambition, energy, climate and circular economy policy goals under the European Green Deal. The main changes include expanding its scope, strengthening permit requirements, and adding measures to foster innovation (EP, 2023).

The EU Biodiversity Strategy and Farm to Fork Strategy set the "goal of zero pollution from nitrogen and phosphorus flows from fertilisers through reducing nutrient losses by at least 50%, while ensuring that there is no deterioration in soil fertility". Since 2022, EC and the Joint Research Centre collaborate for developing a comprehensive strategy for managing nutrients sustainably in agricultural and environmental contexts. Against this backdrop, the **Integrated Nutrient Management Action Plan** (INMAP) focuses on addressing the challenges related to nutrient management, particularly concerning nitrogen and phosphorus. Key objectives of INMAP include:i) gathering scientific knowledge and evidence; ii) developing integrated management approaches; iii) enhancing policy development, and iv) promoting stakeholder engagement and cooperation (JRC, 2023).

1.6. Indirect Protection of Soil in Other Legislations and Gaps in Soil Policy

Although there is no overarching legal obligation in EU law to avoid soil degradation or ensure soil remediation, current legislation provides 'indirect' protection measures and enables remediation to various aspects of soils. The table below, derived from the work conducted for the Impact Assessment of the SML Directive, provides an overview of soil protection currently in place, spanning from sectors such as air, water and nature to chemicals and the indirect prevention of soil contamination. For instance, the Nitrate Directive aims to protect surface waters and groundwaters against pollution from agricultural sources. It requires Member States to set up Nitrate Vulnerable

Zones and action programs for risk areas. Even if the Directive does not have a soil-specific focus, the practices promoted contribute to reduce run-off nutrients thus indirectly limiting pollution, acidification and erosion of agricultural land.

During the stakeholder consultation, two reports were mentioned in relation to indirect soil protection. One expert pointed to the "*Impact of the CAP on sustainable management of the soil*" evaluation study. The study highlights how the lack of a common definition of soil health and the limited availability of data complicates the assessment of how soil-related practices – fostered by CAP instruments – have (or have not) contributed to soil/soil components quality. Among other recommendations, the study advocated the establishment of an EU framework ensuring common definitions of soil, soil threats, sustainable soil management, and soil conservation agriculture, considered as a "*prerequisite to fostering coordination among Member States or regions and for facilitating the spread of conservation practices in the EU, but also research on those practices and the design of instruments to support conservation practices*".

In line with this reference, another expert mentioned the recent Court of Auditor study "*Special report 19/2023: EU efforts for sustainable soil management – Unambitious standards and limited targeting*" directed to assessing whether the Commission and Member States have made effective use of EU tools – specifically the CAP and the Nitrates Directive – in managing agricultural soils and manure sustainably. The report recognizes that cross-compliance standards on soil and manure management have the potential to address threats to soil because they apply to 85% of the utilised agricultural areas. "*However, the requirements set at the Member State level often call for limited changes in farmers' behaviours and lead to limited improvements in farming practices. The Commission did not assess the level of ambition in its annual reviews of the measures taken by Member States to implement good agricultural and environmental conditions. Furthermore, very few Member States have evaluated the contribution of cross-compliance to ensuring sustainable soil and manure management*".

In conclusion, existing environmental legislation lacks a systematic approach to preventing and managing soil sustainably and comprehensively. The absence of a clear definition of soil health and agreed-upon monitoring parameters complicates the enforcement and monitoring of indirect soil protection across EU policies and Countries. Therefore, the proposed Soil Monitoring Law (SML) is essential for effectively enforcing and monitoring interrelated legislation. Its review process will also be fundamental to address current shortcomings in soil descriptors' selection and thresholds and improve the structuring of soil districts as monitoring units able to comprehensively represent all soil types and account for local variations.

Table 6 – Soil relevant policy legislations– own elaboration based on the information contained in the Impact Assessment of SML (Annex II) Colour coding differentiates between direct impact (green) and indirect impact (blue)

		Prevention of pollution	Pollution remediation	Soil Carbon - organic soil	Soil carbon - mineral soil	Soil sealing	Erosion	Compaction	Soil biodiversity	Excess of nutrients /nutrients	Salinisation	Acidification	Water retention
Horizontal	Environmental Impact Assessment Directive (EIA) 2011/92/EU												
	Strategic Environmental Assessment Directive (SEA) 2001/42/EC												
	Environmental Liability Directive (ELD) 2004/35/EC												
	Environmental Crime Directive 2008/99/EC												
Air	National Emissions reduction Commitment (NEC) Directive												
	Ambient Air Quality (AAQ) Directives												
Water	Water Framework Directive (WFD) 2000/60/EC												
	Groundwater Directive 2006/118/EC												
	Floods Directive 2007/60/EC												
	Nitrates Directive 91/676/EEC												
	Urban Wastewater Treatment (UWWT) Directive 91/271/EEC												
	Drinking Water Directive UE/2020/ 2184												
Waste	Waste Directive 208/98/EC												
	The Landfill Directive 99/31/EC												
	The Sewage Sludge Directive 86/278/EEC												
Nature	Habitats Directive 92/43/EEC												
Industrial Emission	Industrial Emissions Directive (EU) 2010/75												

	European Pollutant Release and Transfer Register (EPRTR) Regulation												
Specific subsances Regulation	The Pesticides Directive 2009/128/EC												
	Fertilising Products Regulation 1009/ 2019												
	Market and Use of Biocidal products Regulation No 528/2012												
	Plant Protection Products Regulation 1107/2009/EC												
	Mercury Regulation 2017/852												
	Persistent Organic Pollutants Regulation 2019/1021												
	REACH Regulation												
	Plant Protection Products Regulation 1107/2009/EC												
	Biocidal Products Regulation EU) 528/2012												
Climate	European Climate Law Regulation (EU) 2021/1119												

2. Assessment of Data needs: Stakeholders Views

2.1. Methodology for Stakeholders' Consultation

The results of the policy framing presented in Section 1 informed the identification and selection of interviewees, with a particular focus on ensuring representation from the policy fields associated with soil management and conservation. The list of candidates was enriched by project partners and by employing snowballing as some respondents suggested other experts or stakeholders who could contribute to the study. The activity targeted mainly EC officers as well stakeholders active in the European arena and representatives from the potential AI4SoilHealth "users" ecosystems – such as experts from national research institutes, farmers and landowners, and member of the industry network – were included. Between October 2023 and-March 2024, a total of 29 stakeholders were interviewed (see Annex I the interview protocol and Annex 2 the list institutions from the respondents). Interviews were conducted in a semi-structured manner with the aim of exploring what kind of data information was perceived by the interviewees as most needed to enhance the relevance of soil into his/her work. The interview protocol, drafted in agreement with project partners, guided the consultation process but the approach provided flexibility to capture additional insights on the topics discussed. The interviews were conducted online, in English, and had an average duration of approximately 45 minutes. Due to busy agendas and limited availability of some interviewees, in a few exceptional cases we received written contributions rather than conducting oral interviews. While most of the interviews were individual, some respondents chose to be interviewed alongside colleagues who possessed complementary competences. To integrate the institutional/technical perspective on soil with an environmental social sciences and humanities angle, a leading environmental scholar was interviewed in view of ensuring AI4SoilHealth's data-driven research supports land workers and avoids becoming isolated in a theoretical bubble of data. This specific interview was carried out using a different set of questions and it is reported in the Section 3. To facilitate the in-depth analysis of inputs collected, the interviews were recorded with the consent of the interviewee. Interview transcripts were then cross-analyzed to identify recurrent themes, risks, knowledge gaps and underlying policy questions. For the sake of confidentiality, only the affiliations of the interviewees will be disclosed, while their sensitive data, such as names and surnames, will remain anonymous.

Table 7 – Distribution of the institutional affiliations of the interviewees

European Commission, Agency and Research Centre	Academia and Regional Research Centers	Regional Authorities, Land Managers, Famers and Owners Associations	Networks, Associations, and SMEs working in the environmental field
DG CLIMA	UK Centre for Ecology & Hydrology	ELO: European Landowners Association	Agroecology Europe
DG SANTE	Imperial College London	No Till Bulgaria	SAE Innova
DG AGRI	University of Oulu	EUSTAFOR - European State Forest Association	European Compost Network
DG ENV	Università degli Studi di Napoli Federico II	Regione Toscana	Sustainable Soils Alliance
EUROSTAT	Research Institute of Organic Agriculture – FiBL		Soil Association Exchange
Joint Research Center			Soil Association
European Environment Agency			

2.2. Findings from Stakeholders' Consultation

2.2.1. Key soil health-related policy goals should be pursued.

Q1 - What are the key soil health-related policy goal(s) in your area of expertise?

“From a policy standpoint, soil health is considered through multiple lenses, and reaching a consensus on its definition and management is an ambitious yet critical endeavor.”(EC Officer)

Summary - Accounting for Pre-Identified Goals and Challenges of Setting New Ones

Not surprisingly, most interviewees pointed to the Soil Monitoring Law (SML) as the main reference for soil health objectives, targets, and territorial scope. The SML’s alignment with the Green Deal and the EU's Soil Strategy was collectively recognized given all initiatives share visions for a goal of achieving soil health and promoting sustainable soil management by 2050. The SML proposal was praised as a cross-collaborative effort among Directorates-General which serves as a model to the current proposal for forest monitoring legislation. All respondents echoed Mission Soil’s goals to implement 100 living labs to support transitions to healthy soils by 2050. Interviewees highlighted how soil intersects with various goals set in different policy areas for mitigating climate change, protecting nature, eliminating pollution, and ensuring a sustainable food system.

The challenge of defining "*healthy soil*" due to variables such as the presence of living organisms, soil biological activity, and the capacity to retain nutrients was expressed on multiple occasions. The intricacies of what constitutes a healthy soil are underscored in the SML. There is a general consensus around the notion that emphasis on soil health should be on fostering sustainable production practices, which are essential for the well-being of ecosystems. However, this overarching role of soil providing various ecosystem services, makes it challenging to set universal soil health parameters that apply to the varying biophysical conditions found across different regions. In Europe, this complexity is amplified due to the stark contrasts in environments such as the Mediterranean and Boreal regions.

From a policy standpoint, soil health is considered through multiple lenses, and reaching a consensus on its definition and management is an ambitious yet critical endeavor. Efforts are underway through various research projects (e.g. AI4SoilHealth) to establish a foundational understanding of soil conditions and to create a baseline for further study and improvement. This will be further pursued through structured consultations with stakeholders. In terms of short-term objectives, a shared priority is the adherence to a framework of principles, some of which have a direct impact on soil health e.g.promoting recycling synergies. Reaching an agreement on these principles will be instrumental in guiding policies and actions toward reaching soil health goals within the broader context of the ecosystem.

Qualitative analysis

Shortlisting soil health targets and linking them to actions

Among the targets mentioned by respondents are milestones present in the SML and in other legislative measures connected to soil health. The targets that have been seen to be frequently considered and urgently met are carbon sequestration and the reduction of pesticide usage. The European Commission is developing incentive models to promote carbon storage in soil, which is vital in combating climate change. However, there are concerns as measuring long-term carbon storage in soil is complex and as a result, "*the Commission's communication on sustainable carbon cycles by 2028 intends for all farmers, foresters, and land managers to understand their carbon or greenhouse gas (GHG) emission balances. A unified system for monitoring and reporting such values is anticipated to facilitate the verification of emissions and removals. This assessment system could also underpin financial incentives through mechanisms such as the Common Agricultural Policy (CAP) and, possibly, the emission trading system or voluntary carbon markets. Ideally, individual carbon balances from farms and forests should contribute to national GHG emissions inventories*".

One expert highlighted the importance of linking targets to actions stating that "*Our primary aim is to acknowledge and back those who manage land in their efforts to enhance soil quality. We encourage a practical approach, focusing on achievable enhancements rather than setting unattainable objectives. There is frequently a disconnect between policy aspirations and the actual situation on the ground, underscoring the necessity to harmonize the language used and the expectations held to ensure successful execution*".

The targets mentioned by interviewees were included in the analysis presented in Section 1.4 soil-health related targets

The time factor: Developing policies that account for nature's reaction speed

Across respondents, there is a consensus on the need for foundational work to technically define what healthy soils will entail by 2030 and up to and including 2050. Although a collective definition process is paramount, several respondents stressed the need not to delay action noting that "*Shifting from a short-term focus on annual soil yields to a long-range perspective is essential. We must consider the soil's legacy for future generations, emphasizing sustainability over decades, not just years. Monitoring the soil's slow response rate is challenging and potentially costly, which is where AI technology could prove beneficial*".

One of the hurdles encountered is accounting for the varying time horizons associated with different soil types; for example, sustainable changes in agricultural soils might manifest faster than in forest soils. This raises the question of how to consider the slow pace of natural change, which can span decades, when establishing policy goals and objectives. To address this temporal challenge, both policies and targets need to be designed with a flexible and long-term perspective in mind, accommodating the natural timelines of ecological processes and recognizing how the time required for soil improvement and ecosystem recovery can vary considerably depending on the type of soil and land use. This temporal awareness requires setting incremental targets that allow for the gradual progression of soil health and incorporate adaptive management strategies to adjust to the pace of nature's responses.

Territorial scope: Improving cooperation on data sharing and integrating bottom-up approaches to account for different landscapes (and how AI can help advance monitoring). Most interviewees work at the EU level and thus pointed out the complexities of cooperation and data usage across various territorial scales in the context of soil health and environmental policy. To effectively implement policies using soil indicators, it is crucial to enable these indicators to work at various territorial ranges and to ensure that these are readable, understandable, and usable across a variety of landscapes. Monitoring systems for soil indicators should also be built considering data ownership issues.

The use of pesticides was identified by one respondent as a topic influenced by territorial variations. They said "*Globally, we have the COP 15 target and the Sustainable Development Goals (SDGs). Within the EU, the Farm to Fork strategy outlines pesticide reduction targets by 2030. However, as IFOAM's report indicates, relying on sales data for indicators may not be accurate. Nationally, countries like France have detailed plans such as ECO PHYTO, which is currently being updated. Similarly, the German Federal Environment Agency has developed a methodology to refine target indicators for risk reduction*".

The effort to integrate different levels of implementation (national/local and EU level) is apparent in soil carbon assessment. One interviewee stressed how "*At the European level, we aim to create a map reflecting the current state of our soils and forests. At the individual level, we are exploring ways to monitor, report, and verify carbon and greenhouse gas emissions for farmers and foresters. The overarching goal is to integrate these levels. Currently, our approach is top-down. For example, in a member state like Italy, with its extensive farmlands and forests, we rely on multiplying the standard emission factor. Our ambition is to shift to a bottom-up approach, where we can accurately determine* *the carbon balance for each plot of land. Ultimately, we envision implementing this alongside other biodiversity indicators to create a geographically explicit registry of land activity*". This vision aims for result-based outcomes and acknowledges the need for advanced methods in source sampling and for the introduction of AI for effective data management. All respondents agreed on the need to embrace AI tools to yield comprehensive snapshots of soil performances.

One interviewee noted: "*Soil is a challenging area to gather statistical data in, particularly because valuable information is often held by farmers. It's important to remember that soil issues extend beyond agricultural land; there are multiple non-agricultural factors affecting soil health that must be taken into account. My involvement in the LUCAS (Land Use and Coverage Area frame Survey) project included coordinating a team where we introduced soil sampling as a method to observe changes over time. This is an important tool, as it allows us to analyze soil samples on a larger scale, assessing soil health and trends—whether they are improving or deteriorating. However, soil data analysis is currently outside the scope of what we can provide in terms of statistics. Regarding the modernization of migration statistics, we have recently incorporated changes in fertilizer statistics. Starting next year, these statistics will have a legal foundation, but currently, they are managed at the national level. The ultimate goal is to establish coordinated and comparable fertilizer statistics across Europe. We are also looking into the inclusion of organic fertilizer data, but this is still in the preliminary stages, requiring extensive groundwork*".

2.2.2. Enabling policies, legislation, and tools in place

Q2 - Which legislation or policy interventions are currently in use, or under consideration, to help achieve the goal(s) you previously identified regarding soil health?

> *"Initiatives aimed at improving soil health should embrace a holistic approach that recognizes and integrates all these interconnected elements." (EC Officer)*

Summary - Stretching policy domains to embrace ecosystems holistically

An evaluation of the roles played by current frameworks in promoting soil health goals and targets was the starting point for respondents to consider future policy interventions that could enable a holistic approach to soil health. Interviewees emphasized the need for comprehensive awareness across the sectors of agriculture, climate, and biodiversity to support coherent policy frameworks and the integration of ecosystem services, whilst also pointing out the growing importance of trade policy and international collaboration in environmental efforts. A qualitative analysis of the findings underscores the necessity for ensuring coherence across current regulations and acknowledges the potential of technology, such as AI, in the advancement of soil health monitoring systems. Overall, the overview of possible regulatory improvements calls for a more inclusive approach that considers all interconnected elements of the ecosystem.

Qualitative analysis

Depending on the experts' background, different interventions contained in policy initiatives were mentioned. One expert cited the EU Soil WIKI as a rich database containing all legislative and policy interventions linked to soil health, including their transposition to national levels.

Balancing regulation to harmonise agricultural performance and ecological conservation
Some interviewees considered the carbon certification for carbon removals and the implementation of soil monitoring laws as crucial aspects of our environmental efforts with one respondent stating that "*While these measures do not impose strict rules, they do raise awareness about the importance of soil health. I believe that these measures should be included under both climate and agricultural policies*". Additionally, regulatory frameworks, such as the water and nitrogen directives, are essential. In countries such as Belgium and the Netherlands, there are significant conflicts regarding strict rules on nitrogen emissions by farmers. Reducing nitrogen emissions is considered indispensable due to their impact on neighbouring nature reserves, which can lead to consequences on soil health in these areas. The conflicts arising from these regulations emphasise the challenging balance that must be maintained between agricultural productivity and environmental conservation.

Comprehensive and coherent legislative approaches

Several respondents stressed how the adoption of a comprehensive perspective when addressing soil-related problems is essential. These respondents felt that by *"Concentrating exclusively on one aspect, such as agriculture, water, or biodiversity, is a fundamental error. By doing so, we fail to capture the true nature of soil health. I've observed how the use of artificial intelligence in agriculture fails to account for water-related concerns, both in terms of its quality and availability, as well as issues relating to biodiversity. Pollution aspects are often neglected, and sometimes the focus is narrowly placed on climate factors, primarily due to the relevance of carbon. However, this approach is flawed because it artificially separates elements that are inherently connected. Soil is an integral part of the environment, as is biodiversity. In my view, initiatives aimed at improving soil health should embrace a holistic approach that recognizes and integrates all these interconnected elements*".

In line with this view, other respondents highlighted the importance of *ensuring coherence across current policy initiatives (i.e. regulatory and financial) before enacting upon new legislation*. One interviewee suggested moving upstream to semantic agreements, calling for attention in defining ecosystem services stating that "*although not always explicitly framed as policy goals, references to ecosystem services are implicitly present, albeit too broadly described, in various legal instruments".*

Keeping up to speed with trade policy and international perspectives

The extent to which trade policy should be considered is an open question. In reference to the need to avoid negative impacts to soil worldwide, reference was made towards the *soil footprint calculator* which is currently being developed by JRC. One respondent reported being part of an expert team devoted to developing consumer footprint calculators, looking to synchronise efforts with other existing tools. They said that "*historically, we have not given much attention to trade, yet its significance is escalating and demands our consideration*".

In addition, the international and development perspectives were also identified as worthy of attention. S*oil's importance is sometimes overlooked, even in international development policies, despite its significance, especially in regions where soil quality is a major issue".* It was noted that *"There's still much work to be done in raising awareness about soil's importance, but recent events, such as the mention of soil by Blinken at Davos, indicate a growing awareness of the crucial role of soil management in addressing global challenges like demographic changes and conflicts".* The EU is at the forefront of much environmental policymaking and plays a pivotal role in formulating UN conventions which address biodiversity, the fight against desertification, and climate change. The critical role of soil is becoming increasingly critical in these arenas. For instance, the adoption of the Global Biodiversity Framework by the Convention on Biological Diversity and the subsequent formation of the Soil Biodiversity Observatory underscores the growing importance of soil with one respondent noting that "*These elements are fundamental for the EU agenda and receive thorough consideration in our work*".

Overview of policy initiatives mentioned by respondents was included in the analysis in Section 1.

2.2.3. Conceptual frameworks to shape a soil paradigm

Q3 - Under what framework would you normally think of soils?

Summary – Valuing soil through environmental economics, One Health approaches and natural capital 'marketing'

There was no agreement among the experts interviewed on the most appropriate conceptual framework to address the issue of soil health. Despite the lack of a consensus, there is a shared understanding of the value soil has through interdisciplinary methods, suggesting that there is a need for an approach that encompasses economic, ecological, and health perspectives. This highlights the ongoing debate and the necessity for collaborative efforts to establish effective strategies for soil conservation and sustainable use. The insights coming from environmental economics and informed assessments of human activities coupled with the advancements in biotechnologies can fast-track towards an impactful public-facing and policy-inspiring communication on soil's value and its inseparability from ecosystem services and human health.

Qualitative Analysis

Among the points raised by interviewees when encouraged to think of shaping a soil paradigm are:

- **The challenge of using frameworks to communicate effectively with the public and consumers.** Some respondents stated that *"soil isn't typically on everyone's radar. Soil stakeholders are familiar with the technicalities of terms such as 'ecosystem services' and 'natural capital', but translating such concepts for the general public can be challenging. I believe the idea of natural capital is key to helping widely convey how soil essentially supports the ecosystem services derived from various ecosystems. In support of the latter, the Soil Strategy heavily emphasizes ecosystem services provided by soil. We're also exploring the UN Ecosystem Accounting System to address the evaluation of these services, which is crucial*." On a similar note, one interviewee recognised the challenge of "*making environmental services more valued and marketable"*.
- **Need to focus on possible responses rather than drivers of change.** In relation to the DPSIR (Driving forces, Pressures, State, Impact, and Responses) framework, more than one expert acknowledged the usefulness of the framework for analysing environmental issues and human activities. However, its traditional application was deemed to be too narrowly focused on the production side, emphasizing quantity over quality. Such narrow focus can exacerbate current debate if applied with a limited perspective. This was acknowledged by one recipient who said "*we are well aware of the necessity to produce sufficient food to support the growing global population. However, the conversation should not revolve solely around food quantity. The quality of the food produced, and the methods of production are equally important*". Historically, the DPSIR framework has been mainly geared towards understanding the immediate drivers and impacts of environmental degradation, potentially

at the expense of deeper insights into sustainable practices. It has often emphasized the *'driving forces'* related to production needs, while *'responses'* have not always been adequately addressing the balance between demands and the sustainable management of natural resources. One expert referred to the SAPEA report as a relevant application of a conceptual methodology able to identify lock-ins in the food systems as well as potential responses.

- **Calibrating environmental economics to quantify external soil-related costs**. Several experts interviewed reflected on the challenges of capturing the full cost of soil degradation and pointed to the limitations of current economic frameworks when it comes to environmental accounting. The struggle to quantify the externalized costs of soil-related issues is a common obstacle in environmental economics with one interviewee stating that "*when assessing the costs associated with soil, we encountered a significant hurdle: half of the externalized costs are unquantifiable*". This underscores a critical flaw in relying solely on economic evaluations. Such an approach invariably overlooks vital aspects, particularly the long-term impacts on human health and ecosystem services. The conceptual frameworks available are somewhat generic and lack specificity. Some respondents identified the environmental accounting system as the most promising tool for addressing these complexities. However, a few experts felt that "*economic green accounting*" would be a preferable term and considered valuable to refer to systems overseen by the Food and Agriculture Organization (FAO), which is responsible for developing methodologies in this field. Others mentioned systems based on United Nations directives, such as the System of Environmental-Economic Accounting SEEA system, or the National Resource Damage Assessment (NRDA), which align with international agreements and legislation.
- **Accounting for the wide spectrum of soil functions - from the impact on human health to climate change implications**. One expert stressed the inseparability of ecosystem services and human health, which is at the core of the One Health approach stating that "*the interdependence between ecosystem services and human health is undeniable and should be the focal point of any holistic health strategy. The One Health initiative recognizes this connection by integrating environmental, human, and animal health; however, it often falls short by primarily concentrating on the development and distribution of vaccines. While vaccines are an essential aspect of disease prevention, One Health encompasses much more. A compelling example of its broader scope is the research into the relationship*

between human gut microbiota and soil microbiota. This connection is profound; our health is significantly influenced by our microbiome, which in turn is affected by the bacteria present in the soil where our food is grown. The balance of soil microbiota directly impacts the quality and safety of our food, and thus, any imbalance can have repercussions on human health". Advancements in biotechnology, such as soil DNA analysis, are on the horizon and with the help of artificial intelligence, there is potential to unlock a deeper understanding of soil health and its direct implications for human well-being. Soil DNA analysis could revolutionize our approach to managing soil ecosystems and, by extension, our health.

2.2.4. Unintended negative impacts on soil health due to policies

Q4 - To the best of your knowledge, are you aware of any activities or legislation within your policy domain that are causing damage or unintended consequences to soil health? How could this be addressed?

"While I wouldn't say our specific policies cause damage, I am aware that other policy areas - like the common agricultural policy and urban strategies - may have consequences for soil health". (EC Officer)

<u>Summary – Aligning multiple policy ambitions without creating new problems</u>

All interviewees agreed that while no policy design sets out to cause soil degradation, the unintended consequences that some policies have on soil are evident. In some policy realms – such as Common Agricultural Policy (CAP) – the extent of these positive (and/or negative) impacts on soils is hard to evaluate due to a lack of agreement on definitions and data collection methods. There is potential for the EU-wide framework proposal on soil monitoring to contribute to the monitoring of policies' impacts. Although Member States are responsible for reporting, a lack of comprehensive data hinders the EC's evaluation of policy effectiveness.

Weak policies which fail to adequately address soil management issues can also be highly detrimental. A report from the European Court of Auditors criticizes the low ambition and effectiveness of existing soil and manure management standards, noting how Member States often set minimal requirements that are incapable of significantly altering farming practices.

The implementation phase of policies is considered by many respondents to be just as crucial as the design phase, with a need to enable adaptable, region-specific strategies and ensure reduced administrative burdens for farmers. There is also a desire to rethink the role of agriculture by including metrics reflecting sustainability and social values, which should go above and beyond mere market and productivity targets.

Several interviewees shared concerns about inconsistencies, such as those reported in the implementation of the Nitrates Directive. Delays in European Commission action plans suggest a limited commitment to addressing these discrepancies.

Experts also cautioned that urban planning and infrastructure projects often overlooked adequate soil protection measures, resulting in the loss of high-quality agricultural land. Another warning shared relates to the knowledge gaps on the long-term impact of contaminants, such as heavy metals, and antibiotics which threaten soil and water quality and could impact human health and ecosystems. Research and policy measures are identified as the primary tools to tackle these risks, with an emphasis on addressing emerging threats such as microplastics. Experts also questioned carbon trading practices, noting how these often rely on funding from polluting industries, and as a result placing the cost on consumers. Additionally, respondents have criticized the imprecise accounting methods employed in carbon sequestration, emphasizing the need for accurate measurements. Concerns were also raised regarding the potential trade-offs in carbon farming, such as threats to biodiversity and food production, suggesting a need for more comprehensive ecosystem management strategies. One expert proposed the evaluation of unintended consequences through a systems perspective to gain a better holistic understanding and navigate the inevitable trade-offs between conflicting objectives. For example, promoting organic farming could inadvertently lead to an increased use of copper, an organic pesticide that can persist in the soil and cause environmental issues. Overall, the array of concerns collected underscores the complexity of aligning multiple policy ambitions without creating new problems.

Quantitative analysis

Interviewers shared consistent opinions over the unintended consequences that some policy areas may have on soil health and agree on the complexity of assessing to what extent this occurs. The improvement of policy coherence across areas, ensuring that positive and negative effects on soil are appropriately acknowledged and evaluated, is part of the SML objectives.

Impacting policies, subsidies, and interventions

The formulation, along with the implementation, of Common Agriculture subsidies was mentioned by several respondents – remanding to the analysis carried out in two reports . Expert points to the studies "*Impact of the CAP on sustainable management of the soil*", "*Special report 19/2023: EU efforts for sustainable soil management – Unambitious standards and limited targeting"*.

Nonetheless, the issue lies not only in the formulation of policy but also in the way policies and financial instruments are implemented by Member States. One respondent said that "*If policies are not carefully crafted and implemented, they can inadvertently cause harm. For example, overly rigid rules could scare farmers into ploughing grasslands unnecessarily. The issue isn't limited to direct damage; inconsistent agricultural practices can also threaten soil health. Practices such as tillage and pesticide application may produce varying effects, influenced by soil type and local conditions. Achieving the right balance is essential! A strategy that is effective in one region may not work in another. This underscores the importance of soil analysis to enable informed, location-specific decision-making"*. Special attention to supporting land workers in policy compliance was deemed necessary with another interviewee stating that "*It's crucial for these policies to work effectively for farmers, without burdening them with excessive administration and controls. We need a more reasonable approach to policy implementation. Additionally, providing support and guidance to farmers through intermediary organizations or associations could help them navigate the complexities of these laws and regulations more effectively*". Finally, one expert mentioned the need to rethink the role of agriculture and recognize food as a human right – which can't be measured only in terms of price, quantity, or efficiency – in line with the SAPEA opinion on Towards a sustainable food system.

Balancing ambition with implementation: The Nitrates Directive case

Some respondents noted the complexity of answering questions about unintended consequences to soil health due to its connection with policy ambition and implementation. One recipient articulated that "*Member States are facing implementation challenges with the Nitrate Directive, highlighted by delays from the European Commission in releasing an integrated nutrient management action plan. Such delays indicate a possible lack of political commitment to thoroughly address soil health. Although these policies don't intentionally damage soil, the level of dedication to soil conservation is a critical aspect to examine*". In line with this view, another expert stressed the gap between policy ambition and implementation: "*For instance, while the Nitrates Directive may be a very good legislative act on paper, it is very difficult to implement on the ground and to report on relevant impacts. A better definition of responsibilities, also regarding the collection and management of relevant data, might be useful"*. As the subsidiary principle applies to the Nitrates Directive, Member States have the responsibility of implementing this policy with strong guidance and cooperation with the EC through national plans and programmes. Concerning this requirement, the Court of Auditor report highlights that a significant portion of Member States did not present sufficient data on key manure indicators in their 2016-2019 reports on the implementation of the Nitrates Directive. However, in its response note to the study, the EC noted, among other comments, that there is no current obligation for MS to report this data on nutrient balances under the Nitrates Directive. The obligation for Member States to collect data on nutrient balances will become effective as of 2026 under regulation EU/2022/2379.

Soil-sensitive urban planning and infrastructure development

Experts expressed concern regarding the extent to which Member States and regions/local authorities ponder soil protection in urban planning and infrastructure development projects "*From an Agroecology perspective, the misuse of prime agricultural land due to urbanization and infrastructure development is a significant concern. This leads to irreversible soil loss and pushes agriculture onto less fertile marginal lands"*. Another recipient, using their experiences from Italy, said that: *"I can identify two main issues, primarily related to the specificity of the [Italian] legislation on the matter. Firstly, there's a significant problem with urban planning laws, like the PUC, which unfortunately largely ignores soil-related concerns. This is a serious issue because urban planning should take into account soil characteristics. Secondly, pollution regulations, such as Legislative Decree 152, are quite coarse in identifying polluted areas, resulting in ineffective restoration efforts and additional damage to the soil".* Another expert from the UK also raised that the construction industry has issues with carbon loss and soil waste, and pointed out that the Sustainable Soils Alliance has been working with the industry to bring soils into construction legislation.

Antibiotics resistance

Respondents stress how the existing knowledge gap has hampered the evaluation of how contaminants and the persistence of antibiotics affect soil in the long term. Some respondents stated that "*the excessive use of fertilizers and the contamination of animal manure with heavy metals and antibiotics pose serious risks to soil and water quality. We lack comprehensive knowledge about the long-term effects of these contaminants and the persistence of antibiotics in the soil, which raises concerns about potential impacts on human health and the environment. It's crucial to address these issues through rigorous research and policy interventions to safeguard soil and water resources for future generations*". Frontier research on new-risk substances and antibiotic resistance is advocated with one interviewee stating that *"I'd say most of these factors are known, perhaps with new high-risk substances (i.e. microplastics) and antibiotic resistance being more prominent*".

Is carbon trading good enough or do we need something more radical?

Some experts voiced uncertainties, if not a degree of scepticism, regarding the effectiveness of current approaches to ecosystem services, carbon sequestration, and the associated financial models of carbon trading. "*I believe it's crucial to adopt a broader and more sustainable strategy in managing ecosystems to ensure long-term viability and environmental integrity*". In line with this statement, one respondent argued that "*The current model involves compensating land managers or private owners for maintaining healthy forests which, in turn, provide a range of benefits, including timber, clean air, water purification, and biodiversity. However, funding sources are a matter of concern, as the money often originates from industries responsible for pollution. This situation creates ambiguity around who is actually bearing the costs, as it's the consumers of these industries who ultimately finance the conservation efforts*". Additionally, accounting methods were questioned: "*I worked on carbon farming and have seen how the challenges in tracking and measuring carbon removal are quite high. The methods used in LULUCF (Land Use, Land Use Change, and Forestry) are like an estimate of estimates. It is important to measure accurately and not sell something based on estimation*". What if carbon farming became widespread? "*If carbon farming, through policy support and market incentives, were to become something at scale, this would open to the consideration of trade-offs and whether certain practices pose a threat, for example, to biodiversity. Food production and biodiversity are two main aspects that are often mentioned as trade-offs within the carbon farming sector*".

Working from a systems perspective and understanding trade-offs

One expert argued how, given the conflicting policy objectives, adopting a systems perspective would help evaluate lock-in and consequences. "*Conflicts can arise between different policy objectives. On one hand, there's a goal to reduce pesticide usage, and on the other, there are Green Deal ambitions to cut down on non-renewable energy and lower carbon emissions*."

2.2.5. Best-case scenarios for soil health (and how to recognise them)

Q5 Assuming favorable circumstances, what are your expectations for the development of soil health over the next 20 years?
Which specific metrics or measurements would you prefer to use to monitor and demonstrate successful outcomes for your policy area?

"I don't anticipate drastic changes in soil health practices, but rather a refinement and consolidation of existing information (Land user Representative).

Among the expectations for the future of soil health shared by interviewees is the achievement of Mission Soil's objectives, reaching the goals for healthy soil by 2050. Achieving this target would signal a paradigm shift in society, with a multi-actor involvement process in which scientists and policymakers agree on a consolidated definition of healthy soil. Such cohesion in interpretation would allow for a nuanced approach to what is considered unhealthy soil, including an understanding of where these issues are prevalent, resulting in targeted actions. In this promising scenario, decision-support tools are created to provide evidence-based policies. Concurrently, farmers can access tailored recommendations on sustainable management practices that are grounded in their specific context. Soil scientists and technicians across Member States use consistent methodologies and measurement standards whilst improving data quality and predictive modeling. Soil technicians and farmers typically cooperate in the collection of farm-level data which is then shared across countries and throughout the EU. Scientists, farmers, and industry should typically work together to promote soil as a socio-economic value. Citizens – from landowners to decision-makers – are expected to be soil health-aware during their daily activities.

Qualitative analysis

Expectations for the development of soil health in the next decade and beyond varied depending on the interviewees' backgrounds and experiences. However, when foreseeing scenarios, a vast majority of respondents stepped out of their role to consider the perspective of soil actors as target '*users*' of future soil health destinations.

United under a common soil health definition

A best-case future soil scenario is one in which scientists and policymakers agree on a consolidated definition of healthy soil, adopting a nuanced approach to what is considered unhealthy soil. The latter approach will allow the localization of these 'unhealthy' areas, followed by targeted actions: **"***Currently, the broad statistic of 60 to 70% of soil being labeled as unhealthy is prevalent, but we need a more nuanced approach. I envision different categories explaining precisely what types of unhealthy soils exist, their locations, and tailored actions for each category".* Policy-wise, decision-support tools are created to inform the formulation of place and evidence-based policies: "*It's not just about regulation; it's about understanding the diverse issues faced by forests, agriculture, and urban areas. We can't regulate everything in the same way, especially considering the varying timelines* *and pressures different environments face".* As another expert noted: "*In general, we need operational tools, such as decision support tools, that can comprehensively address the complexity of soil systems. As for specific metrics, there isn't a one-size-fits-all solution. Despite numerous projects and decades of research, we lack a unique metric. Instead, we must adopt a multi-parametric approach, considering various quantitative and physically based parameters. This helps mitigate issues like recalibration and ensures broader applicability across different geographical areas".*

Place-based and integrated recommendations on sustainable management practices for farmers

Some experts expect the SML's implementation to power systematic, statistically significant measurements of all soil parameters affecting ecosystems. This would help untangle the complexity that soil currently possesses creating a comprehensive database able to consider all possible variables and offer indications to land-owners on more sustainable management practices. *"This type of resource would allow us to use an app to determine the best practices for growing, say, tomatoes in a particular soil type, considering all regulatory requirements. Although such capability is not available today, it is achievable through a structured approach, potentially aided by artificial intelligence. I emphasize this vision because it's crucial to integrate soil health with other factors like temperature, humidity, and even food quality and traceability. Projects are already beginning to link human health with environmental conditions. If we can also connect this to the traceability of food originating from fields with thoroughly measured attributes — using satellite imagery, pesticide usage records, etc. — and further integrate this data with water quality and infiltration figures, we could have a telling picture. The analytical challenge will be significant but, from my understanding, comprehensive integration is essential and will be key to advancing soil management and health"*. ore than one respondent expressed the expectation to integrate soils and soil maps in association with crop planning, water flows, and different land use planning.

Soil scientists and technicians across MS use consistent methodologies and measurement standards, improving data quality and predictive modeling

For some respondents, working to improve what is already available would be moving forward: "*I don't anticipate drastic changes in soil health practices, but rather a refinement and consolidation of existing information. We need to address the inconsistency in soil analysis results between labs to improve data quality and predictive models. Consistency in measurement metrics will be crucial for* *accurately tracking changes in soil health. I find it amazing that even for the same soil sampling, for the same parameter, two labs can deliver massively different results!"*. In addition, although new practices are desirable, continuity in approaches must be pursued: "*We can't overlook the importance of consistent measurement standards. Even as we implement new practices, we must ensure we're measuring the same parameters consistently over time to truly gauge their impact on soil health. It's about maintaining continuity in our approach to effectively monitor and improve soil health outcomes*". Similarly, another interviewee noted how "*Achieving standardized approaches across Europe would be ideal, but we're still far from that goal due to the diversity of perspectives and methodologie*s".

Soil technicians and farmers cooperate in the collection of farm-level data to be shared across countries and throughout the EU.

"*I think it would be better to have statistics also on a regional and even local level, but it is key to cooperate with farmers to access farm-level data"*. Currently, soil indicators are related to the work of EUSO, JRC, and EUROSTAT and often also depend on each Member State. "*For the future, we hope to adopt a European point of view. We aim to delve deeper into local scale/farm data. There is some data from LUCAS, but it is not an exhaustive survey. We need to determine key elements for farmers to monitor and test independently to assess the state of biological activity in the soil; for example, before and after pesticide use"*.

Scientists, farmers, and industry cooperate to promote soil as a socio-economic value

Some respondents approve of complementing quantitative data with qualitative evaluations of soil management practices: "*I propose shifting the focus to management systems, assessing how soil is managed to address compaction and enhance organic matter levels. Unlike absolute values, these indicators provide a more nuanced and manageable approach to evaluating soil health. It's crucial to acknowledge the practical limitations of purely quantitative approaches and recognize the value of assessing soil health through a combination of measurable management practices*". In line with this, "*Regarding the parameters to monitor this success, I would integrate the functional biodiversity in the monitoring system. Biodiversity should be measured not only by counting taxa but also by understanding how the soil "web" works, what is the role of each taxa, and how this connects within the food web and the all ecosystem. So, I would start from "functional biodiversity" by encouraging policies that focus also on connecting the soil aspect to the human impact of this ecosystem. Shifting from a threat approach to a functional approach".* It was mentioned the need for building a 'critical consensus' around soil which is not centered purely around carbon and for creating a e also talks about a new narrative which is compeling for land managers to join up and put their best efforts into working for soil health.

From landowners to decision-makers, soil health awareness should guide daily activities Several respondents have commented on the need for soil to get into the spotlight across various domains: *"Our monitoring efforts aim to demonstrate a reduction in pressures on soils over time. We have several indicators, such as areas experiencing unsustainable erosion and urban expansion, that highlight soil health issues. So, a combination of heightened awareness and tangible evidence from monitoring campaigns would be beneficial to increase overall awareness on soil***".** On a similar note, one respondent noted that a shift from the past would also require "*increased attention to soil health by farmers, decision-makers, and technicians".*

Rooting for Mission's Soil's success

The desirable vision for soil health is for restoration and preservation thanks to the achievement (and further improvement) of Mission Soil's proposed targets and the successful implementation of the many initiatives related to soil health: "*My ambition is that all these policies and initiatives for soil health will succeed so that we will recover degraded soils in Europe and have mostly healthy soils*". What would be possible signs that a desired vision for soil health has become a reality? One expert mentioned the up scaling of carbon farming initiatives as a sign of success: "*I guess that we can measure success by seeing carbon farming spread across the EU. If all EU farmers are applying some sort of carbon farming, receiving some sort of carbon farming scheme, this means we will have demonstrated that there is interest, and the market is happy to pay for this as a mitigation action*".

2.2.6. Type and format of soil data needed to inform policies

Q6 -What method(s) are being used to obtain and gather relevant data? What supporting data and materials - such as metadata and documentation - could facilitate you to use and comprehend future products (e.g., maps, code)?

"…When people see a red area on a map where they live, they tend to pay attention." (EC Officer)

Summary – Employing AI to establish comprehensive soil health baselines and integrate data

Respondents emphasized the necessity of creating accessible and standardized baselines to effectively measure soil health changes over time. Establishing such baselines, which integrate both past and current data, is crucial for monitoring soil (and subsoil) health, certifying sustainable practices, and informing policy. Projects like AI4SoilHealth, which employ artificial intelligence and machine learning, will be instrumental in creating these comprehensive baselines. To accurately track soil health dynamics, it is important to produce time-series maps through regular data collection, as required by the Soil Monitoring Law. These maps can reveal trends like pollution spread or soil degradation. By doing this, it should raise public awareness and help shape policy decisions. These data sets can support the elaboration of *geographically detailed and location-specific assessments.* Experts also highlighted the importance of combining satellite data with local soil samplings for a more precise assessment of soil health. While satellite images provide a macroscopic view, field samples offer the detailed information necessary to validate and refine these observations. Finally, respondents advocated the need for time-series maps to be both informative and actionable, providing insights to navigate strategies based on mapped scenarios. Transparency in data collection methods, standardization across countries and laboratories, and effective communication are unanimously regarded as key to enabling informed decisions and actions by soil managers and policymakers.

Qualitative analysis

More than one respondent highlighted the importance of establishing accessible and standardized baselines for effective soil health assessment. A baseline provides a reference point against which future developments can be measured. Comprehensive soil health assessments depend on the availability of such baselines, which are informed by both past and current data. Research projects like AI4Soilhealth, which leverage AI and machine learning, can play a significant role in synthesizing vast amounts of data to establish these baselines. Benchmark values are not only critical for ongoing monitoring but also for certifying soil health practices and informing sustainability initiatives. One respondent shared a desired outcome for the future: "*I hope that in 5-10 years, things may be very different given the greater availability of specific data, and projects like AI4SoilHealth can be very helpful to set baselines and support a comprehensive evaluation of soils' condition. In our certification proposal, we introduced the idea of standardized baselines*." The availability of extensive data sets can support the elaboration of "*geographically detailed and location-specific assessments – see the references contained in the updated Land Use, Land Use Change, and Forestry (LULUCF)* *regulation and other recent policy frameworks, especially the Infrastructure for Spatial Information in the European Community (INSPIRE) directive*".

As part of the considerable efforts to outline these baselines, the following aspects deserve consideration:

The key importance of demonstrating dynamics

Regular data collection, as mandated by the SML, enables the creation of time-series maps illustrating trends and changes - such as the spread of pollution, the degradation of soil quality and the dynamics in land use planning - more effectively. The ability to visualize these alterations can increase public awareness and influence policy decisions by clearly showing the time-span effect. One interviewee remarks "*the challenge lies in demonstrating changes over time. This is where the soil monitoring law becomes crucial, as it requires Member States to collect data regularly. Many policy-related questions, such as the extent of diffuse pollution, remain unanswered due to lack of data and inability to show changes".* Another interviewee supported this view recognizing the need for "*static mapping of soil types, texture, etc.*" but also stressing the urgency for *"dynamic maps able to support farmers with daily indications; for instance, informing on changes in the water content due to yesterday's rain, evapotranspiration and the like".*

The need to combine satellite observation with local soil sampling

Maps derived from satellite data are incredibly useful for providing a broad overview of soil conditions and identifying areas or environments that may require further attention. However, as noted by two experts, satellite observations must be validated and enhanced by ground-truthing through local soil sampling. Detailed field samples analyzed in the laboratory can provide the granularity necessary to confirm and refine satellite-derived maps. This combination of large-scale remote sensing with localized sampling is crucial for accurately assessing soil health, including changes in soil carbon content, moisture levels, and other key indicators. *"Firstly, there is the need to increase the accuracy of maps, without extrapolation and interpolation of sparse data. At the same time, soil needs testing. We need to go to the field, take half-kilo samples, send them to the lab, conduct chemistry analyses, and determine the characteristics. Currently, satellite technology can only provide limited and often imprecise data".*

Several respondents recognized the potential and relevance for optical means of observation, like satellites, drones, and images to be used, for example, in monitoring agricultural conservation practices, like cover crops, no-tillage, agroforestry, or landscape elements. However, remote observations should always be complemented by soil sampling to obtain a telling picture. As one interviewee pointed out: "*It's essential to gather site-specific data and management information, including nutrient balances. Understanding the inputs and outputs, especially of nitrogen, is crucial to prevent environmental issues like eutrophication. Soil monitoring is vital, and while I advocate for soil analysis, a more systemic approach integrating state, management practices and changes observed could reduce costs and potentially incentivize state support.*

Maps as empowering tools for action, not just information

Several respondents stressed how the provision of information is just the first step to enabling individual and collective actions. Specific conditions were mentioned by respondents as prerequisites for sparking a successful engagement process based on the information shared. On one hand, the process of collecting and structuring soil health data should be transparent. "*I think it is important to assess how data were collected, what methods were used, and document if any equivalence and/or conversions of indicators were performed*". On the other hand, for data to be meaningfully integrated, there is a need for standardisation: "*Every country has its standards, its own way of measuring things, and it's tough to compare. Even within one country, if you apply the same method and send the same soil sample to different laboratories, you will get different results. So, there is still a huge amount of work to be done in achieving standardization*". Once harmonized data sets are available, effective knowledge sharing and communication strategies can transform information into actionable insights: "*Soil managers should be provided with useful evidence to make informed decisions about what is beneficial or detrimental for their soil*". "*I believe it is about translating data-based knowledge into something easily communicable so that policymakers can grasp it quickly and utilize it effectively. Communication is key. We often have sufficient knowledge (although scientists always stress the need for further research), but struggle with striking the right chords and getting people to think, 'OK, I understand this, and now I'm ready to take action*'".

2.2.7. Geographical information spatial coverage

Q7 - Would you require details about aspects of soil quality for the entire EU or limited to a specific geographical area?

"Having the data doesn't mean making decisions! It's about being informed and capable of evaluating the European challenges. I believe the confusion between having data and making decisions also stems from territorial conflicts between regions, nations, and the European Union.

Let's explore a concrete example: suppose in five years, we see that all sites where the soil compaction has increased haven't changed, and no measures have been taken for tractors. Well, that becomes a problem at the European level, not just for individual farms. We need to conceive a policy to favor the transition from heavier to lighter machines. And only Europe can do that! It plays a crucial role" (EC Officer)

Summary – Different degrees of granularity for different policy elements

The data collected and methods employed at EU-level generally aim at local and regional scales, while outlooks at national and EU/European scales may be generated by aggregations of available datasets, possibly in high-resolution. Data availability is crucial to inform actions on soil health at multiple scales. However, different needs have been identified depending on the policy stage and specific competences. While all respondents agree on the importance of farm-scale data for local governance and targeted interventions, there is debate around the granularity that EU-level data should be, with opinions varying depending on respondents' professional roles. While detailed farm data might be relevant for assessing the impact of EU market based instruments (policy evaluation) in view of incentivizing targeted soil health improvements (policy formulation), policy enforcement at EU level may derive greater advantages from data aggregated at regional/national level, useful to identify national policy implementation, situation of non-compliance with the legal obligations and general trends.

Qualitative analysis

It was noted how "*data collected, and methods employed at EU level are generally aiming at local and regional scales. However, projections to national and EU/European scale may be aggregations of available datasets, possibly in high-resolution. Even with 8 km in-situ sampling programs, 100m or finer maps can be predicted with possible limitations to the quality of trend detection*".

Farm-scale level insights

Most respondents agreed on making information at farm scale or enterprise/industry scale available to local governance and actors to enable informed policy making and individual agency. This granular approach provides valuable insights into individual practices and allows for the implementation of targeted interventions to address specific soil health issues at their source.Additionality, it allows to identify those farming/entreprises that are over-performing or underperforming. This aspect has been agreed as a priority action to be implemented. Comments included: "*Although I find it crucial to monitor local effects because neighboring fields can have very* *different soil types - which makes it challenging to get information – I believe complementing local data with European scale aggregation is useful".* Similarly, one respondent noted: *"I prefer soil health data at the local scale because it's more practical and relevant for individuals and businesses. However, I understand the need for data aggregation in policymaking, which should still accurately reflect regional differences and avoid overgeneralization".* One expert from a farmers organization noted the relevance of landscape level observation for the promotion of incentive schemes that target specific areas: *"We think farm-scale monitoring is important because we advocate for schemes that need to be monitored at the lowest scale. Although as an organization we do promote a kind of more landscape type of approach where it's the rural community that gets involved, directly addressing carbon farming as a real activity (e.g. 'I do cover crops' or 'I do no-till'), a link to higher scale operations is desirable. For example, if I need to use an organic fertilizer, maybe we need a composting facility to come to this region. It's really about transforming the community but going beyond simple monitoring."*

For national policy, having a *representative sample for every square kilometer is adequate. When dealing with severe soil degradation or erosion, data at a sub-field level becomes necessary. For areas smaller than one kilometer or at the field level, we must rely on some form of modeling, which inherently involves uncertainty.*

EU policy standpoints determine the granularity required

There is consensus on the need for national and European aggregated data to support higher level decision-making. The key question that needs discussing is: to what extent should European data be granular and should this be the most appropriate scale. Respondents, as expected, shared different perspectives, reflecting their professional standpoint either in policy evaluation, formulation, or implementation.

Policy and research formulation needs

Experts reported how detailed data could be a basis for moving from a command and control-type legislation to one supporting change management: "*From a policy design, research, and engagement perspective, it is important to access data that enables a more differentiated discussion in all fields. Having farm scale data would allow not only to obtain a snapshot of the current situation but would also promote change management. This point is central to avoid generalisations and to enable a system that rewards the front runners and starts incentivizing the laggards. Including the farm scale is indispensable to understand that performances of farmers*". For example, one expert mentioned how information at the parcel level is needed to monitor CAP standards related to *peatland protection which contain a ban on some types of plowing.* Similar considerations on the value of small-scale data are deemed valid for the GAEC (Good Agricultural and Environmental Conditions) directed at promoting conservation actions.

Policy enforcement concerns

Other interviewees suggested that a combination of detailed and aggregated data might best serve the purpose of policy enforcement: "*At the EU level, we mostly concentrate on policy implementation, and we recognize that soil management occurs at specific, localized points, making the collection of ground-level data essential to grasp local dynamics. While farm-scale surveys provide granular insights, our focus is often on the aggregated picture, such as practices within particular bioclimatic farming systems. This approach to defining soil areas helps us identify general trends in soil management while still considering exceptions. Overall, to shape our policies effectively, we require a synthesis of both detailed local data and broader aggregated information*".

One expert noted the core dilemma of balancing costs against the added value: "*If a system becomes overly complex and costly, we need to assess the kind of data it can feasibly provide. There's always a decision to be made between the ideal data we crave and what we truly need to know, which involves prioritizing our data "wish list." In my view, obtaining data that is statistically reliable at a regional level, would be a significant advancement. From there, we could consider supplementing with local-level data. It's about taking it one step at a time".*

Policy impact assessment requirements

For some experts, having farm level information at EU level would enable the evaluation of soil health challenges and improve the assessment of current legislation: "*We require comprehensive data at EU level, extending even to the plot scale. For example, it's important to know the number of farms and plots that have experienced degradation or improvement in recent years and to what extent. Without this information, higher level decisions cannot be effective. It's not just about deciding on actions but also assessing whether legislation is achieving its intended impact. Looking at averages can be misleading, as they can suggest everything is fine or problematic without indicating where to intervene".*

2.2.8. Soil data stratification/interpretative or reporting unit

Q8. What is your preferred interpretive or reporting unit to assess your policy goals?

Stratification is essential for understanding soil trends. One cannot grasp these trends without categorizing them through at least three criteria: land use type, soil type, and climate zone. (Research and Academia Representative)

Summary – Addressing multiple dimensions to grasp soil complexity

Interviewees stressed the importance of using multiple parameters to assess soil health, with a majority indicating that soil types, climatic zones, and land use should be used as key factors. Depending on policy areas and soil use, additional parameters may be discussed and implemented. For instance, specific considerations for agriculture must include crop types, climate-related variations in cropping, and pesticide use. The need to incorporate economic and administrative dimensions, like farm types and management practices, is also highlighted as instrumental in informing sustainable practices. As such, a multi-dimensional approach to data collection is recommended to account for the unique combination of co-existing features and meet the distinctive needs of different ecosystems and farming practices. Given the extensive time and resource-consuming efforts to collect stratified data, there is general agreement on the possibility of using existing data sets, such as those from the JRC, as a starting point.

Qualitative analysis

A combination of parameters is needed to understand soil health in its entirety. The features most frequently mentioned by interviewees are soil types, climatic zones, and land use type. In addition to these core elements, other parameters can be added to capture trends relevant to specific policies. "*All these stratifications provide important and useful information, depending on the type of policies under consideration. The fact that management systems differ depending on the soil you're working with points to the interconnectedness of processes".*

Parameters influencing farming practices

Agricultural soils, for example, require the collection of crop and zone type-related information. "*When assessing agricultural practices, it is crucial to consider both crop types and climatic zones. The frequency of cropping and pesticide use can vary significantly with climate; for example, Cyprus can produce three potato crops annually, potentially tripling pesticide use compared to Ireland, which only produces one due to its different climate. At the same time, Mediterranean-like climates may experience higher pest pressures, necessitating more pesticide applications. A comprehensive assessment needs to account for these variations in climate and pest pressures, as well as encompass differences in individual crop cultivation".*

The case of forestry ecosystems

One interviewer emphasized the importance of focusing on habitats or land cover when conducting environmental analysis for the forest sector, particularly due to the diversity of soil types and management systems that are characteristic of these areas. "*The need to separate statistical indicators is crucial, as exemplified by forest connectivity metrics, where the inclusion of urban areas like big cities can skew the results. To effectively understand and address environmental challenges, a logical and sector-specific approach is advocated, ensuring that strategies are informed by an accurate understanding of the distinct characteristics of each ecosystem*."

Land management variables

When considering the promotion of sustainable changes in land stewardship, many respondents underlined the need to connect landscape-related parameters (such as soil type and climate zone descriptors) up with economic-administrative indicators such as farm types, management practices, and administrative units. "*During the execution of transition analyses, it's imperative to not only consider the scale of the landscape or nation but to delve into the nuances of how individual farms are managed. Global land use models tend to adopt a top-down approach; however, there is interest in translating these broad results into actionable insights for specific regions, taking into account the unique management practices present. Understanding the initial state of the soil and the type of soil is a critical aspect of this analysis. An in-depth look at the current situation, or the baseline, at the time when new soil management approaches are adopted, especially at the farm level, provides invaluable context for evaluating the effectiveness and impact of such transitions in soil management". For instance,* one respondent pointed out how "*interesting it would be to explore the differences between organic and conventional farms regarding soil carbon levels - this comparison could provide valuable insights into the potential benefits of organic farming practices for soil health and carbon sequestration*."

Accounting for time and resource-consuming data collection efforts

While recognizing the usefulness of gathering data on land/soil management practices at the EU level, there is agreement in flagging the time-consuming and expensive nature of such activity. There is also a debate regarding the degree to which this should be a national and/or local endeavor. "*Obtaining highly detailed information on soil management practices at the farm level would require extensive sampling or exhaustive questionnaires that may be impractical to implement. However, the Joint Research Centre (JRC) possesses comprehensive data on soil types and habitats. The* *suggested approach involves leveraging the statistical data available and mapping it, layering these maps to observe patterns and changes. This method allows for the analysis of changes over time, such as shifts in soil management practices within farming communities, without the need for overly burdensome data collection from individual farms".* In line with this approach, some respondents suggested a 'bottom-up' feeding, where parameters can be added depending on the specific needs of the farmers and landowners.

2.2.9. Frequency and timeliness

Q9 - How often does data need to be updated to ensure you can meet your policy objectives and reporting?

"The baseline should integrate legacy data, with a standard 5-year update cycle complemented by annual updates to meet the requirements of natural capital accounting. Additionally, we must ensure the ability to issue emergency reports when unexpected events occur, such as the detection of a new pesticide or a volcanic eruption. For these situations, having access to 'dried and frozen' archives has proven invaluable" (Research and Academia Representative)

Summary – Towards a structured (and flexible) monitoring framework

Many interviewees align with the SHL's vision to update soil health data every five years, a period deemed appropriate to balance the slow rate of soil change with the urgent needs of policymaking and the analytical ones of scientific research. This paced approach allows for the regular collection of sufficient data to establish a baseline for soil health main parameters and support the creation of a legacy data archive. At the same time, the necessity for more frequent updates, possibly on an annual basis, for certain soil parameters is acknowledged. Moreover, there is a recognized need for emergency reporting capabilities in response to unforeseen events such as new pesticide detection or natural disasters. Respondents tend to suggest a flexible monitoring framework, offering long-term insights into soil quality trends while also allowing for real-time data collection for specific parameters and supporting rapid responses to extreme events.

Qualitative analysis

Most respondents approve and echo the SHL's indications on performing soil measurements every 5 years.

Five is a good number

The selected timeframe is considered suitable for establishing a baseline reference and building an archive of legacy data. One interviewee state "*there seems to be convergence on a five-year interval for updates, which strikes a comfortable balance as soil changes quite slowly…and if it would allow to predict trends over a longer term, such as 10 to 15 years, it would be even more beneficial. I wouldn't advocate for overly frequent updates since they could generate confusion".* The time interval proposed seems to provide a compromise between the needs of policy and those of soil scientists. Monitoring should be timed to produce policy-informing data geared at feeding policy cycles every 3-5 years. Thus, "*from a policy perspective, updating assessments every three to five years would be more practical to evaluate the effectiveness of implemented policies and ensure the desired impact is achieved".* In addition, the proposed timeframe considers the costs and benefits of creating these types of comprehensive systems.

Temporal requirements for certain parameters

Although the 5-year timespan is generally well-received, a need for more frequent – even annual – updates for specific parameters is recognized, along with the ability to carry out specific investigations when an unexpected event occurs. "*The Baseline should integrate legacy data with a standard 5-year update cycle complemented by annual updates to meet the requirements of natural capital accounting. Additionally, we must ensure the ability to issue emergency reports when unexpected events occur, such as the detection of a new pesticide or a volcanic eruption. For these situations, having access to 'dried and frozen' archives has proven invaluable".* The temporal variability required by different parameters is largely recognized: "*When it comes to updating soil health data, it depends on the parameter we're looking at. For instance, erosion requires more frequent updates, especially considering its vulnerability to climate events like floods or fires. On the other hand, parameters like organic matter or compaction may change more slowly and can be updated on a longer timescale*."

Flexible, regular, and adaptive updates

The overall demand emerging from the stakeholder consultation is for the implementation of a flexible monitoring approach backed by a baseline, regularly updated every five years, and capable of offering an understanding of how actions impact soil quality over time and track changes. Specific parameters, such as nutrient applications, should be complemented by annual or even real-time updates. In addition, the monitoring system should be adaptive and able to detect and respond to extreme events.

2.2.10. Climate and land use considerations

Q10- To what extent are climate change and land use changes currently considered in the development of soil health interventions/measures?

"*We've initiated dialogues with the farming community as we aim to safeguard permanent grasslands as much as possible, viewing this through the lens of climate mitigation and overseeing it via conditionality. Yet, this approach raises some concerns because market forces often play a significant role. In certain countries, where farmers express a desire to transition from grasslands to arable lands, it becomes a contentious topic. Livestock concerns are also integral to these discussions, considering the anticipated impact of climate change on livestock farming*". *(Research and Academia Representative)*

Summary – Urgent call for strong and holistic EU-led soil conservation policies

The EU lacks binding soil conservation targets, often relying on voluntary national strategies. Given the impact of land use and management on multiple global and European dimensions, experts call for increased integration of land use considerations across EU policies, emphasizing the need for a holistic approach that balances energy production, food security, and environmental protection. Although climate change concerns are addressed in various EU policies, experts push for a broader view of soil health that encompasses biodiversity and other ecosystem services, not just carbon storage. Current climate strategies are seen to be lacking in urgency and being over-reliant on voluntary actions. A stronger policy approach is recommended, engaging Member States and the agricultural community, considering market forces and ensuring fair cost-sharing along the market supply chain.

Qualitative analysis

In 2012, the United Nations committed to halt soil degradation and rehabilitate damaged soils by 2030. A pledge that aligns with the Sustainable Development Goals (SDGs) outlined in the 2030 Agenda for Sustainable Development. SDGs 11 and 15 specifically advocate for sustainable urban development, combating desertification, and reversing land degradation.

Global concerns for land management are national responsibility

Despite the SDGs aims, the European Union currently does not have obligatory targets for land consumption and soil sealing. Yet, the EU's 2030 Soil Strategy prompts Member States to set individual land intake reduction targets for 2030 to achieve a balance between land development and conservation by 2050. It is noted that *“land management remains a national competency within the EU, requiring unanimous consensus for any EU-level action”*. At the same time, EU-developed legal tools assisting environmental assessments, like the Strategic Environmental Assessment (SEA) and the Environmental Impact Assessment (EIA), can enhance the integration of environmental impacts arising from land management and foster the adoption of greener alternatives.

“*Many experts agree that EU policies such as the ones related to transport, energy, and the Common Agricultural Policy (CAP) could be more effective by considering land intake and degradation factors more thoroughly. Implementing binding land intake targets might promote policy coherence efforts.* For instance, the shift towards eco-friendly practices has increased the demand for biomass, highlighting the need for a comprehensive approach to land use that accounts for various needs such as energy, food, ecological conservation, and biodiversity. As one interviewee pointed out, *“it is vital to tackle land use comprehensively, considering the diverse demands placed on our natural resources, including needs for energy, food, environmental conservation, and biodiversity. Ensuring that policies are aligned is crucial, and there is plenty of room and opportunities to enhance land use aspects. Recently, there has been a noticeable uptick in conversations around land use, underscoring the importance of developing more sophisticated strategies to reconcile ecological goals with practical realities, such as maintaining agricultural yields and encouraging varied use of land”.* Another expert pointed out the importance of keeping a global perspective, especially in relation to urbanization trends and soil sealing impacts on soil health: *“In this respect, the JRC’s work on a global footprint calculator is vital as it assists us in determining whether Europe's current stability in land use might be causing environmental degradation in other parts of the world. It's critical to maintain environmental sustainability universally, not just within the confines of Europe”.*

Climate-driven concerns may sideline overall soil well-being

As opposed to the absence of land use considerations, respondents acknowledged how climate considerations are woven into a broad spectrum of sectoral policies. Frameworks like the Nature Restoration Law and the Carbon Farming Initiatives, funded under the CAP, are driven by climate concerns. However, some experts argue for a holistic view of soil health and warn against a climate-reliant emphasis on carbon sequestration that may neglect biodiversity and overall soil well-being.

One expert noted how *"concentrating predominantly on carbon sequestration, creates a risk of sidelining other vital dimensions, such as biodiversity". "For instance, while no-till farming practices can boost carbon retention, they may also depend heavily on pesticides or substances like glyphosate, which could negatively impact biodiversity and threaten the broader health of the soil. It's imperative to take a comprehensive view of soil health that encompasses its diverse functions and not just its ability to sequester carbon in the fight against climate change*".

Similarly, other stakeholders underscore the need for sustainable management practices that address climate mitigation and adaptation while supporting the soil's capacity to offer other ecosystem services. *"Little to no attention is paid to adaptation in soil management policies. It's frustrating to see this disparity, with the climate agenda focusing more on energy-related policies rather than addressing the complexities of land management and its consequences*". Examples shared to showcase the crucial role played by land management in addressing both climate change and biodiversity include practices such as the water-soil nexus to combat water scarcity for crops due to climate change, soil post-harvest restoration, and using lighter agricultural machinery to minimize soil compaction, thus preventing poor water drainage.

Urgent call for enforceable soil conservation policies informed by structured dialogue

Lastly, some experts suggest that while climate change is recognized as a critical issue, the urgency and ambition in policymaking may not be sufficient. Current strategies often promote virtuous voluntary actions but may not delve deeper into enforceable policies. A more rigorous approach calls for a structured dialogue with Member States and farmers and the consideration of market forces to ensure equitable cost distribution along value chains. "*We've initiated dialogues with the farming community as we aim to safeguard permanent grasslands as much as possible, viewing this through the lens of climate mitigation and overseeing it via conditionality. Yet, this approach raises some concerns because market forces often play a significant role. In certain countries, where farmers express a desire to transition from grasslands to arable lands, it becomes a contentious topic. Livestock concerns are also integral to these discussions, considering the anticipated impact of climate change on livestock farming*".

2.2.11. Challenges encountered in accessing soil health information

Q11 - Do you have any problems accessing the soil health information you need? If so, what are the constraints?

"It's a complex issue because, on one hand, you want to enhance our understanding and develop better tools using landowners' data. Yet on the other hand, it's important to maintain trustworthy instruments to ensure that the data collected isn't used to disadvantage the land managers" (EC Officer).

Summary – Improving soil data accessibility and reliability while balancing privacy concerns with research/policy needs

At the EU level, the aim is to "*acquire knowledge of the specific conditions or environmental thresholds that signal a decline in soil health, to the extent that it negatively impacts conservation goals"*. This will require updating the catalog of European methods and enabling an exploration of interconnections such as, among others, the relationship between soil health and biodiversity and soil health's link to water supply. Although interviewees agree on the importance of improving soil data collection and recognize its relevance for EU policy, accuracy and reliability are flagged as challenges. There is a lack of standardization across the EU, making it difficult to compare data across Member States. Country-level data access is hindered by fragmented databases and limited historical records. Intellectual Property Rights (IPR) and privacy concerns further complicate data sharing and usage. Precision in soil data is crucial for field-level agricultural decisions but concerns about data impacting land value and ownership privacy must be balanced with research and policy needs to protect soils as common good. Proposals include adopting selective data resolution systems to maintain privacy while providing detailed data for research and policy. The key to progress is building trust and collaboration with landowners and farmers, respecting privacy, and ensuring data reliability and accessibility for sustainable land management and policymaking.

Qualitative analysis

Interviewees agreed on the need to enhance the way we gather and use soil data. One expert noted that "*While there's a wealth of data available, the challenge lies in ensuring its accuracy and reliability. Many evaluations, especially those concerning land use, are hampered by problems with data collection methods and by the limitations of current modeling approaches. To overcome these obstacles, we must improve the quality of data gathering and foster better communication among all parties involved. While monitoring initiatives are promising, it's crucial to manage expectations and recognize that improvements won't happen overnight. We need to adjust our tools and expectations accordingly to make meaningful progress in soil data accessibility and reliability*". One of the issues mentioned by a monitoring organization aiming to benchmark soil data is the challenge of getting close to the scale needed for benchmarking.

Problematic use of cross-border data

At the EU level, one of the main challenges is the lack of standardization which hinders the comparison and aggregation of soil data across Member States. *"A systemic lack of standardized soil data across Europe complicates efforts to access reliable information. Diverse methodologies and inconsistencies in data collection hinder comparability and jeopardise utilization for decision-making processes. Trust in data integrity and improvement in data collection mechanisms are crucial for enhancing soil information accessibility and reliability*". On a similar note, one respondent noted how "*Despite popular belief, Europe suffers a systematic shortage of soil data. Each country employs different methods to gather soil information, which makes it difficult to compare and standardize the data across borders.*

Limited and fragmented data

At the national level, professionals and landowners often face obstacles when trying to access soil data, struggling to find user-friendly comprehensive sources. The fragmentation of databases and the scarcity of historical records make it difficult to obtain the soil health information they need. The availability of soil data is limited compared to sectors like water protection, where Member States have more extensive data and archive experience. Although some macro-level data might be available, detailed data specific to individual farms or land parcels are often missing. For instance, one expert noted how *"In Italy, accessing historical soil data is a significant issue. There is no unified national database, and, as a result of constitutional changes in the 1980s, regional databases are disjointed. This fragmentation poses serious obstacles for soil professionals, leading to what is considered a national issue for soil-related work. The lack of geo-referenced data adds to these accessibility and analysis problems".*

In addition, data for specific land cover, such as forests, might lag behind both at the EU and Member State levels. *"Currently, accessing forest soil health data presents unique challenges but there is hope ahead for an improved accessibility over the next two decades".* Estonia is noted for its advanced technological approach to soil data, and Poland is recognized for its extensive, publicly accessible, forest databases, especially in the Eastern region. In addition, even when available, farmers and landowners might have a hard time interpreting data: "*While researchers might have access to detailed soil health data and satellite images, such as those from the LUCAS survey, the* *average farmer may not know where to find this information or how to interpret it. This discrepancy highlights the need for more accessible resources for farmers".* More than one experts stressed as farmers and land owners might find it difficult to know what to look for within the data.

Open data and privacy concerns

Many respondents stress how Intellectual Property Rights (IPRs), and privacy concerns add another layer of complexity as some countries may be hesitant to share or commercialize data collected through public funds. The precision and accuracy of available data are particularly crucial at the field level, where agricultural management decisions are made. While broad mapping is possible for certain soil properties, other aspects like texture and contamination levels demand more detailed, region-specific studies due to the variations in landscape characteristics. Interviewees expressed concerns about data privacy, especially regarding soil data linked to land ownership. Finding a balance between open data access for research and privacy is essential, given the need to manage sensitive information carefully, in accordance with data protection rights. "*In many European countries, soil data is personal because it's connected to landowners. This creates problems in using and sharing this information. Privacy issues, especially under GDPR laws, are significant. There's also a market-related concern about how soil data reflecting poor soil quality can lower land values. Moreover, individuals may consider soil data as an asset from which they can profit. Thus, we must carefully navigate privacy and commercial interests in our soil-driven work*".

As open as possible, as closed as necessary

The balance between the fear of privacy breaches and the demand for transparency with environmental data is crucial. One expert mentioned that the challenge lies in harmonizing the understandable emotional response to personal data protection with the absolute need for transparency in environmental data. The resistance around the use of high-resolution satellite data is a telling example. "S*atellite data would be available at a 10-meter resolution, yet here we are still discussing using 250 meters. This issue needs to be solved! We need to be able to utilize the maximum resolution possible. To maintain data confidentiality, access should be adjusted according to specific uses, similarly to how the GPS works".* The solution discussed is to use the highest possible resolution for research, adjusting data access based on the intended use to maintain confidentiality. *"For example, we could mimic the GPS system, which can be precise to the centimeter but is scrambled to show a 50-meter accuracy for general use. This method could also* *be applied to soil data, ensuring privacy when needed but providing detailed data for the purpose of research and analysis".*

Building trust and collaborative relations with landowners and farmers is key to reaching an agreement on data use. " *Confidentiality is the most critical point for producing statistics at both national and regional levels. Privacy is an issue we're currently facing, and collaboration with farmers is essential to gather information on soil samples, which is a central concern in assessing soil health. There is significant national variation on the matter: some countries cooperate willingly and without significant problems, while others consider this type of data confidential*".

2.2.12. Accuracy and precision

Q12 - In your opinion, what degree or range of accuracy and precision is preferable?

Summary – Challenges of setting (and meeting) precision targets

Soil researchers are urged to provide policymakers with details on desirable accuracy and precision in environmental monitoring data. Trend detection requires data that accurately represents diverse geographical areas and accounts for spatial variability. Determining a 'healthy' environment and identifying degradation are complex tasks that vary by location and parameter requiring tailored approaches.

Current legislation demands a measurement accuracy of 5% threshold every five years. Precision must be tighter than the smallest expected change; for example, if soil organic carbon could change by 2% over five years, measurement precision should be at least one-fifth of that. Precision is crucial for trend detection within the five-year reporting cycle proposed by SHL and aiming for one-fifth of the anticipated change is proposed to minimize uncertainty. However, soil variability challenges the feasibility of such precision targets. At the same time, the number of resources required for monitoring infrastructure to meet precision targets has prompted discussions with Member States on the impact of these standards on their monitoring system designs and implementation. The possibility of significant investments or financial strain from increasing data collection points is being assessed, alongside an evaluation of the effects of lowering accuracy requirements and extending the measurement intervals. Variability in database reliability across Europe is noted, with some areas falling below acceptable levels, highlighting the importance of accurate, context-specific data for both policy and practical applications.

Qualitative analysis

In terms of accuracy and precision, there is a call for soil researchers to inform policymakers of the preferable degree of precision. It was noted that to enable accurate trend detection, data must achieve a certain level of representation and stratification, considering the inherent spatial variability of land. Pondering on ranges of accuracy opens to further core questions… "*How do we initially identify environmental degradation or an unhealthy state? What modifications are necessary to attain a "healthy" state? These questions are specific to each site and parameter; therefore, a comprehensive response requires detailed differentiation*".

Lowering the pressure on national monitoring infrastructure

One expert noted "*The legislation mandates measurements to meet an accuracy of 5% threshold every five years. There is an ongoing discussion with the Member States to determine how this precision standard affects the design of their monitoring systems. We are considering whether these precision targets will necessitate substantial investments to enhance the monitoring infrastructure in place, leading Member States to face a heavy financial burden due to the need to increase data collection points. To tackle these concerns, we are examining the potential outcomes of reducing the required accuracy and prolonging the interval between measurements*".

Feasibility of precision targets

As for precision, it has been highlighted that given the 5-year reporting interval proposed by SHL, the precision must be smaller than the potential changes occurring within this period. "*For instance, if soil organic carbon could potentially change by up to 2% over five years, our measurement precision for soil organic carbon should ideally be one-fifth of that change. To be able to identify a maximum change of around 1%, technically it should be one-fifth of 1%. Now, what does that translate to, provided that this makes sense because soil issues are very specific? Taking two samples just half a meter apart could result in more than a 2% variation, raising the question of whether our precision target is feasible. To reduce uncertainty, we must refine every step of the process. Therefore, aiming for one-fifth of the anticipated change should be our target for measurement precision"*.

No simple answer

All interviewees who responded recognized the complexity of this question on accuracy and precision as the context greatly influences the answer. "*For example, a seemingly minor 2% change over a decade can be significant, but we need context to understand its importance. When it comes to soil mapping, accuracy rates across European databases differ notably. Some databases exhibit* *a reliability of just 86%, which is not considered dependable, while others, such as the Ispra database in Italy, achieve an accuracy of approximately 94%, which users generally accept as satisfactory. Therefore, our goal should be to achieve over 90% accuracy, particularly in soil mapping. Maps with lower accuracy ranges are not only unhelpful for farmers but can also lead to adverse outcomes*".

2.2.13. Expectations tied to soil functions

Q 13- From your perspective, what are the essential activities that healthy soils need to perform in order for your policy goals and interventions to be considered successful?

"The EC is not advocating for reducing food, fibre, or biofuel production, but rather promoting a more sustainable approach that balances ecosystem services. For instance, producing food in a way that enhances soil's ability to retain water, sequester carbon, and support biodiversity (EC Officer).

<u>Summary</u> – Contextualizing soil functions and valuing their interrelation

Many experts agree on the key functions of soil, which include producing food, fibre, and biofuels; supplying timber; purifying water; sequestering carbon; providing a habitat for biodiversity and facilitating the recycling of nutrients and agrochemicals. Some interviewees find it valuable to semantically combine the concept of food production with that of fibre and biofuels to highlight the broader ecological role played by soil in catering to the sustenance of all living organisms. Additionally, soil's role in supporting transport and housing infrastructure and urban well-being is noted. All interviewees emphasized how the adoption of a holistic approach to soil health would reflect the interrelation of soil functions. Focusing on one function at the expense of others could negatively impact overall ecosystem functioning. The European Commission advocates for sustainable land management practices that balance ecosystem services and enhance soil's natural functions. Earth observation systems are acknowledged as useful tools for monitoring soil trends, with the caution that precision and accuracy are essential to avoid detrimental side effects. Context and timing are crucial when evaluating soil functions and the impact of pressures as soil health functions vary by region, and certain practices should be assessed in the long term (e.g. pesticides). Data-based analyses are deemed instrumental in guiding policymaking and informing the general public.

<u>Qualitative analysis</u>

There is consensus on the attribution of soil's primary functions: 1) food production, 2) production of fibre, biofuels, and timber, 3) water purification and retention, 4) carbon sequestration, 5) provision of a habitat for biodiversity 6) Recycling of nutrients and agrochemicals.

One respondent stresses the role of biologically diverse soils '*Most importantly, soil is biodiversity. Soil should be biologically diverse in order to perform its function: this includes, at the baseline, habitat quality, water purification, nutrient cycling, and a certain amount of carbon sequestration'* Another respondent underlines the added value of considering the first two functions — production of food and production of fiber, biofuels, and timber — as a single concept, highlighting soil's role in providing food for all living beings and a habitat for the planet's biodiversity. Soil's contribution to supporting infrastructure, such as roads and railways, as well as urban green spaces and overall well-being, was also put forward. More than expert raises the fuction of soil for ensuring just transitions and social fibres.

Balancing ecosystem services based on soil functions

Each interviewee offers unique insights into one or more soil functions, with a majority stressing soil's 'operational' role for food, fibre, and biofuels production, timber provision, or carbon sequestration. Nonetheless, all respondents agree on the adoption of a holistic approach to soil health, recognizing the interconnectedness of each soil function and flagging the long-term dangers posed to overall ecosystem health by concentrating on single soil functions. *"The EC is not advocating for reducing food, fibre, or biofuel production, but rather promoting a more sustainable approach that balances ecosystem services. For instance, producing food in a way that enhances soil's ability to retain water, sequester carbon, and support biodiversity. It's about optimizing land management to suit each soil's characteristics. Regarding monitoring accuracy and timeliness, Earth observation systems could play a significant role by providing regular proxy indicators. While these may not directly reflect soil health, they can indicate trends such as reduced erosion or increased organic matter. This could be particularly useful for shorter policy cycles. However, precision is crucial to ensure that measures aimed at improving one aspect, such as reducing erosion, don't inadvertently harm soil health, for example, by excessive pesticide use*". In line with this view, another expert notes how the challenge lies in "*finding solutions that are an improvement for the environment as a whole: this requires a holistic approach*"**.**

Context and timing

As discussed in previous questions, context, and timing, in terms of the characteristics of soil settings and chronological intervals being considered, are crucial when evaluating soil functions and the impacts of pressures. As regards local context, contingency was stressed: “*Defining soil health is complex and varies depending on regional and local conditions. We need to link soil health with its functions and ecosystem services, but also recognize that issues like erosion may require independent consideration*”. Timing-wise, long-term assessments are considered important: “*It would be incredibly beneficial to examine the impact of pesticides and pesticide residues on soil health, particularly concerning food production. We need to assess the effects they are having — or not having — to advocate convincingly or provide evidence to the public. For instance, we could say, 'We applied this pesticide 20 years ago, and it's still present in the soil! Long-term assessments allow us to determine if practices have no significant impact, substantial impacts, or if the extent of impact remains unknown.*'"

2.2.14. Findings on the state of current soil assessments in place

Q14 -To your knowledge, are the above soil quality aspects currently measured or assessed at the EU level?

"While many of the essential soil descriptors currently under discussion in the SML are determined at the EU level (LUCAS Soil), the methods to describe functions based on these are still limited (e.g., soil water retention). It's also important to accredit national approaches, which are the core pillars for the current European soil knowledge mosaic"(EC Officer)

<u>Summary – Defining data collection, management and use.</u>

The EU lacked a unified framework for soil health, leading to inconsistent measurement methods across countries. While some soil descriptors, like carbon content, are well-developed, others, especially those related to pollution, require more refined measurement techniques. The proposed Soil Monitoring Legislation (SML) seeks to establish a comprehensive system for assessing various soil health aspects throughout the EU. Although there might be room for improvement in the definition of certain indicators, values, and methodologies, the legislation proposal represents a step forward in soil monitoring efforts. Once approved, Member States will need guidance to support the implementation of the monitoring frameworks at national levels. The framework sets out to serve different policy goals and is key to enabling cooperation across policy departments to integrate and complement the needs and experiences of other relevant areas by establishing a clear role for data collection, management, and use.

Qualitative analysis

At the EU level, there isa lack of a common and comprehensive framework capable of reflecting all soil-relevant aspects. "*Local measurements of fields, lands, or watersheds are available...However, the absence of standardized measurement methods across different countries leads to variations in spatial and temporal resolution. What we're missing is a common framework that offers enough flexibility to accommodate diverse measurement techniques from different locations but still allows for comparison and consistent monitoring. While we can monitor changes over time within the same region using matching methods, comparing results across different regions becomes challenging without a harmonised system*."

Filling the gaps in the European soil knowledge mosaic

The proposed Soil Monitoring Legislation (SML) aims to fill this methodological gap by introducing a shared framework to measure the variety of soil health aspects throughout the EU. "*While many of the essential soil descriptors currently under discussion in the SML are determined at the EU level (LUCAS Soil), the methods to describe functions based on these are still limited (e.g., soil water retention). It's also important to accredit national approaches, which are the core pillars for the current European soil knowledge mosaic".* Once approved, Member States will need guidance to support the implementation of the monitoring frameworks at national levels also considering there is room for improvement in terms of indicators and feasibility. "*It's important to allow enough time for implementation and to observe how local governance interprets and applies these indicators.*"

Context-dependent interpretation of indicators Certain indicators for soil quality aspects have been elaborated to a greater extent than others. At the same time, some indicators are more complex to measure and interpret. "*Carbon is the most straightforward indicator and is connected with various aspects of soil health. However, in organic soils, excessive carbon may not be ideal for biodiversity and food production. Nonetheless, measuring carbon provides valuable insights into soil quality. Pollution is another crucial indicator, but it's challenging to measure comprehensively. While nutrient balances and pesticide use may indicate pollution related to food, fibre, and biofuel production, they might not accurately reflect water purification*."

Cross-policy soil monitoring consolidation

The difference in the development of soil descriptors, values, and methods is linked to the extent to which specific indicators are monitored by other soil-relevant policies. For instance, the work on indicators, values, and methodology relating to carbon sequestration has been developed by the revised LULUCF and Carbon Farming Initiatives. Cross-policy collaboration is key to consolidate the soil monitoring framework and consider the needs and experiences of other relevant areas by establishing a clear role for data collection, management, and use. References to soil indicators are somewhat scattered across different regulations and directives, coming from diverse policy areas. "*For carbon sequestration, the LULUCF Regulation serves as the reference point, providing reporting and verification guidelines. When it comes to water purification and retention, the Nitrates Directive and the Groundwater Directive play central roles in assessing the chemical status of water bodies. Additionally, the Habitats Directive addresses aspects related to soil and biodiversity. As for the recycling of nutrients, regulations such as the Fertilizing Products Regulation and the Sewage Sludge Directive are relevant, although some are outdated".*

2.2.15. Possible improvements to soil monitoring systems

Q15 - What change in soil health monitoring systems might help you achieve your policy goals?

"Enhancing our soil monitoring system involves more than just increasing observation depth. Yet, if deeper observation helps land managers with the practical tools they need for better decision-making and improves data quality, then it's a worthwhile endeavor. Gaining a deeper insight into the dynamics of soil changes and their causes is critical for both policy development and on-the-ground practices".(Network Association representative)

<u>Summary – Guidelines and tools to dig deeper</u>

EU stakeholders agree on the necessity for an improved soil sampling system that provides consistent data across Member States. This system should be adaptable, with variable sampling densities tailored to different land uses and soil types. Concerns were raised regarding the current focus on surface soil matters. This narrow perspective may overlook subsoil conditions which are critical for assessing overall soil health, particularly carbon sequestration. Respondents also call for advanced guidelines that address systematic errors and uncertainties in soil data. Specifically, the need for accurate pesticide application data has been highlighted, as current reporting methods are prone to errors. The cost-effectiveness of monitoring tools is also a concern, with a need to balance detailed data collection with financial constraints. Finally, the integration of AI for the generation of accurate real-time land management advice based on comprehensive data is proposed to enhance better decision-making and protect soil health. One point raised is how to ensure the interests and engagement of end-users (farmers, land users) are duly taken into account so that the final product is aligned with their needs and expectations.

Qualitative analysis

United in differences

All respondents agree on the need for a denser and harmonised sampling system, allowing comparability of data across Member States and enabling the detection of soil trends and dynamics. "*Ensuring a denser and harmonized sampling system across Member States would ensure data comparability for EU assessments*".

A certain differentiation based on specific needs is advised: "*thinking in terms of 'soil units', some can be sampled with less dense (sub-)samples, while others may require improved densities*". Sampling needs might vary depending on land use: "*Frequency is also a differentiating issue as a one-size-fits-all approach might not work for agriculture, urban areas, and forests, due to their unique characteristics and interaction timeline*s"*.*

The deeper soil perspective

The need to gain more in-depth information to feed knowledge on the subsoil was mentioned as a priority: "*When assessing soil health, it's crucial to consider the depth of observations. While we may measure increases in carbon in the top layer of soil, it's essential to understand what's happening in deeper layers. If carbon levels decrease in deeper layers despite increases in the top layer, there may not be a net increase in carbon sequestration, highlighting the importance of comprehensive soil monitoring techniques".* Experts also mentioned the risk of over-sampling, focusing too much on the top layer of soil.

Address errors and data uncertainty

A point was made about systematic errors and uncertainties in soil data being underdressed: "*Current guidelines (e.g. for SOC monitoring) are not sufficient because systematic errors are underrated and under-investigated*".

More detailed data

Some experts highlight an unbalance in the widely available data concerning pesticide sales by country and the lack of information on actual application rates of the products and on the consequences of their use. Current tracking methods, which largely depend on farmers' handwritten logs, are error-prone and may not yield accurate data**.**

Balance research desires with cost-effective monitoring systems

Points were made on cost-conscious sampling and monitoring modes. "*Scientists and researchers often desire further data, including more detailed and frequent measurements, as well as expanded analysis and sampling. However, it's crucial to remain conscious of the costs and resources required, both at the EU and Member State levels. We must consider the financial implications and determine who will carry out the monitoring. While it's natural to crave for extensive data, we must balance our desires with practicality."*

Solutions-oriented data and action-tailored communication

Multiple comments were made on empowering soil actors with tools and real-time guidance. **"***Enhancing our soil monitoring system involves more than just increasing observation depth. Yet, if deeper observation helps land managers with the practical tools they need for better decision-making and improves data quality, then it's a worthwhile endeavor. Gaining a deeper insight into the dynamics of soil changes and their causes is critical for both policy development and on-the-ground practices"*. Similarly, it was pointed how "*soil management often goes overlooked, despite its significant potential to alter soil conditions. While we cannot change inherent soil properties, we can determine and implement the most effective management practices for given conditions. Good agricultural practices are well-established and represent the type of management that can positively impact soil health."* Artificial intelligence is bound to play a role in increasing tailored support to landowners: *"Consider ChatGPT: it provides real-time responses to our inquiries! Ideally, landowners should be able to access immediate, reliable advice tailored to their specific soil conditions. This guidance must be based on the integration of all available data. Accuracy and reliability of AI-driven recommendations are crucial"*. Some respondens stress how changes on-farm should be decided upon by farmers. "*Better data should equip farmers with better tools to make these decisions"*

3 Conclusions

3.1 Data needs

As mentioned in the introduction, this brief aims to investigate knowledge and data needs for the efficient monitoring of soils and the elaboration of effective soil-friendly policies. The findings will contribute to feeding WP3 activities directed at creating a robust selection criterion for the assessment of appropriate Soil Health Indicators (SHIs) as part of a probabilistic-based monitoring framework. Especially in relation to WP5, the input from this policy brief will help tailor the tools and services developed by the project, hopefully supporting the delivery of more accurate soil data at pan-EU level.

Building on the framing of soil-health initiatives existing at the EU level carried out in Section 1, the cross-cutting analysis of the stakeholders' interviews performed in Section 2 pinpoints needs and questions that may provide a basis for further reflections on AI4SoilHealth's role in advancing soil-friendly policies in Europe.

This section aims to connect the dots between legislative needs in terms of soil data and challenges identified by soil stakeholders, including soil scientists, to the unanimous selection of representative soil data able to inform effective soil care and protection practices. The figures and tables below offer a visual and schematic synthesis of the conversations around soil health and data needs held with stakeholders. Figure 1 is a word cloud generated by high-frequency words which came up during the interviews. Figure 2 is a Collocates Graph which represents how words co-occur within a certain distance of a target word in a text. This force-directed network graph helps to identify and analyze the relationships and patterns between words, revealing how they are commonly used together in context. In this representation, keyword (in blue) are shown linked to collocates (in orange). The visual tool used to produce this network analysis was Voyant Tool, a free, open-source software used for quantitative content analysis and text mining. Based on the holistic evaluation of insights coming from Sections 1 and 2, Table 3 offers an overview of the current data challenges, the desiderata expressed for soil health data, and what these data might be used for.

Figure 1 - Word Cloud

Figure 2 - Collocates Graph

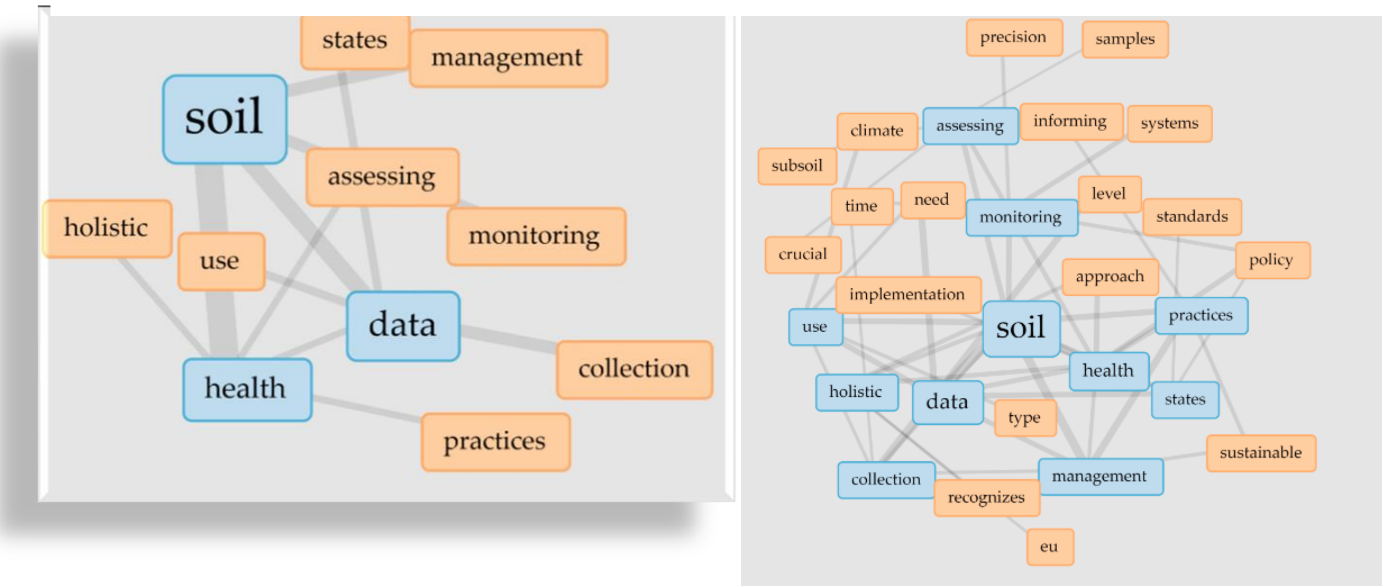
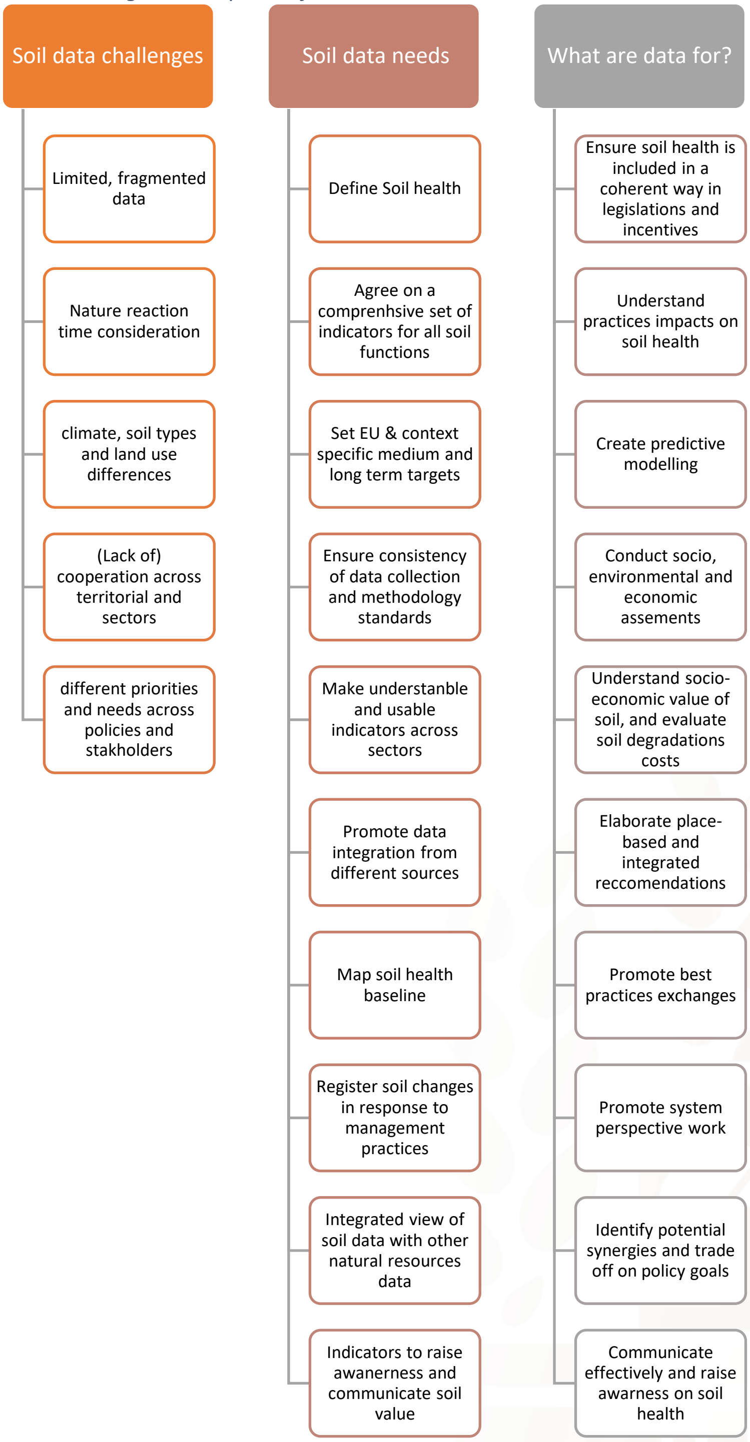


Figure 3 Snapshot of soil health data needs



3.2 Taking the users' perspective: accounting for differences across policy stakeholders

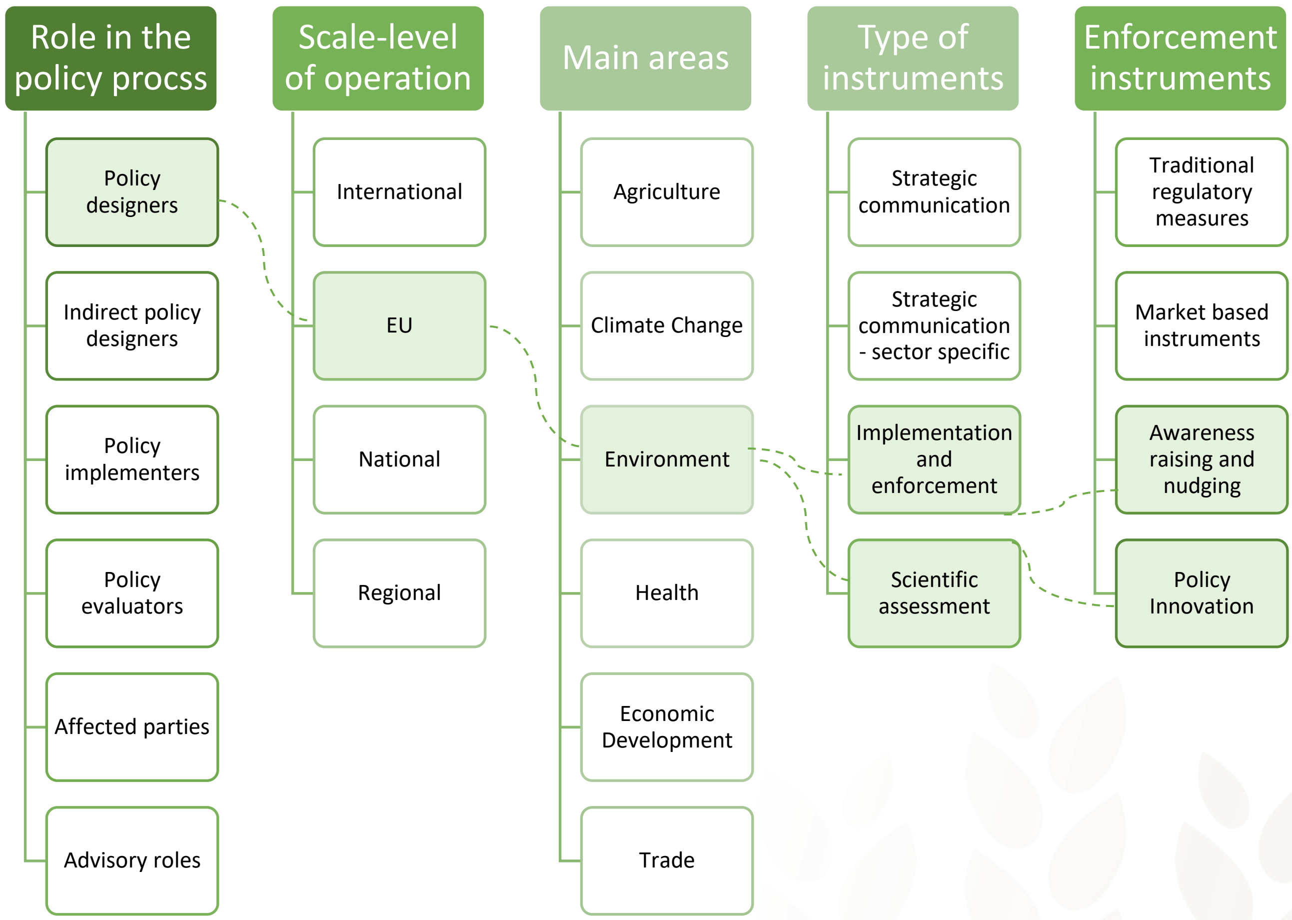
The needs for soil data will vary depending on stakeholders' role in the policy cycles, the scale of their operations, the areas and values of their main policy institutions, and the type of legal instruments they work on. It is crucial for AI4SoilHealth to identify and prioritize the target users in order to adapt and translate the data produced for it to be usable by them.

One potential user group that could benefit from AI4SoilHealth data is policymakers involved in the development and implementation of the Soil Monitoring and Resilience Directive (SML). The data produced by AI4SoilHealth could directly contribute to the implementation of the SML and help fill knowledge gaps highlighted by the directive. Additionally, the data could be used to evaluate wider policies such as the Common Agricultural Policy and support the implementation and enforcement of regulations like the Nature Restoration Law or the Nitrate Directive. Another important user group could be farmers participating in carbon farming initiatives. It is also important to consider users who have opportunities or a need to include soil health considerations in their respective fields of action but may have limited knowledge of soil science.

To make the data applicable to and usable by a variety of actors it should be presented in a user-friendly format and accompanied by clear explanations and guidance on how to interpret and apply the information in their specific contexts based on particular goals and values. Segmenting possible policy users by their role, scale of operation, main areas of work (including priorities, targets, values), type of instruments, and enforcement instruments might be beneficial to ensure the data are easily understandable by identified users. The objective is to be able to leverage data in policy areas where soil health is a co-benefit but not the main focus of the action.

The table below offers an overview of the different types of policy stakeholders, each with specific data needs, and might serve as a tool for AI4Soilhealth to segment potential users.

Figure 4 - Policy stakeholders segmentation (highlighted in green are examples of potential of segments for AI4Soilhealth's ambition)



Finally, it is important to note that environmental approaches to policy and assessment have changed in the last decades and this influences the type of data sets needed. There has been an evolution from specific legislation design targeting an identified source towards an approach able to face systemic causes due to multiple interconnected challenges. Data and indicators are indispensable but should be complemented and integrated with practice-based knowledge, system assessment, stakeholders' participation, and foresight (EEA,2019).

The project could be streamlined by taking into consideration the types of policy and assessments to which the AI4SoilHealth data and framework will contribute. As a litmus test, the paper 'Science, Technology, and Innovation for Ecosystem Performance: Accelerating Sustainability Transitions' has developed three perspectives on future relations between humans and nature – as summarized in the table below (EC, 2023).

Perspective	Main goals	Framework examples
Protecting & Restoring	Preservation of ecosystem by limiting the impacts of human activities	• Environmental Impact Assessment • Model for Biodiversity and ecosystem services
Co-shaping	Simultaneous development of social practices and ecological process toward resilience and sustainability renewal	• Socio-ecological Vienna School • Socio-Ecologic System
Caring with hybrid collective	Establishment of caring relationships in new collectives with humans and other entities on an equal level	• Facing Gaia • Deep Ecology

As highlighted in Section 3.3, monitoring is not just about data, Environmental Social Sciences and Humanities remind us of the link between soil care practices and soil health. The establishment of a reference perspective for AI4SoilHealth might promote the identification of overarching goals for the project concerning the intricate relationship between humans and nature.

3.3 Beyond data: linking Soil Care Practices and Soil Health

Interview with Anna Krzywoszynska*, Associate Professor of Transdisciplinary Human-Environment Relations (University of Oulu)

*AI4SoilHealth structured the interview based on an adapted version of the "seven-questions approach" originated from the work of the Institute of the Future (and further refined by Shell and ICL). This past-aware and future-looking set of questions provided a fertile outline to discuss soil health frameworks from the perspective of Environmental Social Sciences and Humanities. **This article is loosely based on the interview and some quotes have been rephrased for stylistic consistency.**

Environmental Social Sciences and Humanities Remind Us of the Link Between Soil Care Practices and Soil Health

AI4SoilHealth's inspiring chat with Anna Krzywoszynska, a leading environmental social sciences and humanities scholar, highlights the opportunities and risks tied to the application of artificial intelligence to land management and soil monitoring practices. Krzywoszynska advocates a dialogue between science and society, integrating technology with human-environment knowledge systems. Combining scientific-based research with socio-ecological frameworks may help advance *community-driven soil care practices and enhance quality land stewardship, beyond data-driven evaluations of soil performances.*

Our conversation starts from the observation that the ecosystem services perspective seems to dominate the current discourse around soil health, driving scientific research efforts (and funding) and shaping environmental policymaking. This performance-centred perspective precludes a discussion on soil's multiple values and hinders eco-social readings of land issues.

According to Anna Krzywoszynska, Associate Professor of Transdisciplinary Human-Environment Relations at the University of Oulu, the "a healthy soil is what a healthy soil does" discourse narrows the bandwidth of soil research. A functional definition of soil health based on its ecosystem services (i.e. carbon sequestration, biodiversity conservation, water drainage, etc.) limits the scope of research and neglects understanding the relations between soil ecosystems and human society (including, but not limited to the land workers).

When we quantify soil health without considering how different groups interact with it, we lose sight of how actions lead to results, and don't fully appreciate soil's complex social roles. Krzywoszynska's insights are an invitation to pursue technological advancements that are relevant to situated people-land relationships of care, and to ensure that techno-scientific innovation contributes positively to environmental stewardship and the responsible management of natural resources.

Beyond spreadsheets: the risk of monitoring-led actions

The scientific desire to make soil environments and wider ecology calculable and embed governance in a constant monitoring of environmental change risks alienating land workers themselves. In Krzywoszynska's words: "Limiting the discourse on soil health to a checkbox of indicator measurements removes a dynamic involvement [of people] in soil care as a basis for a sustainable society, both ecologically and socially".

In this monitoring-led scenario, enhanced by the increasing availability of AI monitoring tools, the risk is that a hegemony arises in which knowledge systems in land governance and management lose sight of bottom-up knowledge streams tied to land practices coming from the communities who live and work on the land.

If progress in soil care is solely quantified by metrics such as nitrogen pollution or carbon sequestration, without equally valuing community involvement and the pursuit of living in harmony with the land, such quantitative assessments will fall short of capturing the interconnectedness that assures the well-being of societies and ecosystems. Relying solely on technology-driven mediation to shape our future relationships with soils is not advisable.

“The push towards creating Smart Earth observational systems and [incorporating those into governance] decision-making systems, and the development of technologies for constant monitoring and evaluation devoid of sufficient [democratic] involvement, can lead to a disconnect between the people who live and work on the land and the decisions made for that land”, warns Krzywoszynska.

Multiple levels of disconnection with land

Krzywoszynska notes how today's decision-making for soil management and soil health happens with little democratic involvement of the people affected. Standards and target values are set by people whose lives and livelihoods are not dependent on the actual settings being assessed: “Although monitoring [and decision-making] algorithms are a result of human brains, the values being defined are not sourced from actors involved and connected to the land being monitored”.

Disconnection from land becomes a concern on multiple levels. Machine-led land management practices open to the possibility of job loss as the activities of land workers such as farmers and environmental land managers become more automated. However, “it’s not only about losing land-related jobs but about losing the capacity to learn from land and raise questions about the direction of society based on the experiences of change in land”. Removing land workers from the processes of producing knowledge about land, and from the democratic debates about how to shape relations with land, will prevent their meaningful involvement.

Extending the ‘land run by machines’ scenario into a gloomy future, Anna’s dystopian vision is one of “Amazon-owned farms, farmed by Black & Decker robots without direct involvement from people living on this land, in these landscapes”.

Disempowered generations of land stewards

As Krzywoszynska notes, although the artificial intelligence variable is a new entry, the disempowerment of land workers has been around at least since the 1940s, embedded in “farm as factory” models that have dominated the past decades of knowledge production about soils.

She points out that research on good land management practices has long been led by agritech companies and businesses. The support and advisory services made available for farmers have been generally weak and unidirectional, with farmers being seen primarily as consumers of techno-scientific products, and with little investment in farmers’ capacity building. Krzywoszynska believes the failure to provide farmers with a knowledge infrastructure able to help them become better land stewards and perform as educated ecosystem guardians has prevented improvements in quality land management.

In many respects, she stresses, this disempowerment worsened during the Green Revolution, which strengthened the top-down approach, further removing actual farming communities from researching best practices in farming, and preventing the formulation of relevant process questions to intensify their learning about the ecosystem they steward.

The farming population is seeing a demographic collapse, with fewer and fewer people interested in taking up farming livelihoods. Over the past few decades, a positive cultural discourse around agrarian living has failed to develop, and the legacy of this void is a demographic gap in farming where, as the current generation of farmers approaches retirement, a new wave is not ready to take over. "In our recent past, we were unable to deliver a powerful narrative around farming as a valuable enterprise – not a poverty trap – contributing to a happy life - notes Krzywoszynska - and now we are faced with a shortage of farmers and skilled land workers able to cater for land". At the same time, matters of access to land need to be addressed to remove barriers for emerging farmers and enable the development of a more inclusive and diverse agricultural community.

On a positive note, Krzywoszynska feels that the European farming community is actively stepping up to seek a voice in the management of soil-related issues. Recent farming strikes are receiving significant public support, reflecting a growing social recognition of farmers' critical role as the foundation of global food security. Positioning farmers as key players in thinking about soil management empowers them to embrace and champion sustainable land management practices through a constructive dialogue addressing the concerns of both scientific communities and policymaking actors.

Co-production of soil knowledge between science and society

To fill the distance between soil health data and soil care values, Krzywoszynska calls for the co-production of soil knowledge between science and society, especially through the efforts of social movements involved in regenerative agriculture, carbon farming groups, environmental groups, back-to-land initiatives, and many others.

These groups are active at different scales and levels in advocating a dynamic engagement with soil matters to link an understanding of soil health with strengthening community well-being. "Whether at farm, school, community or regional level, the effort is about being proactive in learning about soil and producing knowledge from the bottom-up, with special attention to the role soil can play in a truly 'healthy' society", Krzywoszynska observes.

Krzywoszynska believes a strengthened collaboration between communities of practice and scientists will fast-track soil care and allow science to provide responsive tools to support land management practices and improve ecosystem services overall. In an age of unprecedented innovation applicable to environmental sciences, technology's main priority should be providing farming communities and all other interested groups with tools and assets to improve the ecological functions of soil, thereby empowering them to invest in regenerative farming practices and other environment-conscious activities able to benefit society as a whole.

Supporting place-based research

Research has a crucial role to play in shifting balances and prioritising engagement from relevant actors.
While Krzywoszynska praises the fact that research and innovation projects devoted to soil incorporate societal actors, she notes how the funding mechanism is inherently biased towards research institutions: "The potential for community engagement and social policy-making is weakened by an institutions-focused approach". Krzywoszynska, who is also a Board Member of the Horizon Europe Mission Soil Deal for Europe, believes the generation of research questions on soil solely from the scientific perspective undermines social innovation which is the main mechanism for securing the longevity of Living Labs, as foreseen by Mission Soil. "To ensure Living Labs achieve their potential, the land workers' communities must be central in setting their research agendas. If the structures of Living Labs funding prevent such community-led direction, we will not see a change in the status quo".

For actionable knowledge about soils to be produced, more place-based research is needed. In this respect, Krzywoszynska identifies a need to re-direct money towards place-specific initiatives, looking at soil management and social innovation in specific areas. "Funding should flow towards place-based research seeking to explore (cheaper) small-scale local sustainable growth solutions - Krzywoszynska suggests - The generalising approach, seeking to find one-size-fits-all solutions for anywhere and everywhere, is bound to be less impactful".

Soil's role in re-thinking resource-intensive lifestyles and embracing de-growth

Given the interconnectedness of the soil ecosystem with the evolving global scenario of resource scarcity, geopolitical unrest, and climate concerns (climate refugees, extreme weather events, etc.), land use and management are central to the update of less resource-intensive lifestyles. In Krzywoszynska's words, “A truly green future will require massive investment in the development of both practices and technologies that can actually help us to be less resource-intensive”.

Krzywoszynska recognizes how “de-growth” may be an uncomfortable term and a difficult concept to tackle but underlines the paramount need to reconcile the economy, in terms of the movements of goods and services in society, with a shrinking resource base. Speaking of soil, this means reimagining agriculture, reconsidering access to land, and promoting small-scale land stewardship based on local drivers to develop sustainable food systems in support of socio-environmental justice. Krzywoszynska hints at the potential ‘small farm future’ envisaged by Chris Smaje where small communities involved in good land management systems provide quality everyday living and sustenance to local groups.

There may be different outlooks on the future, but Krzywoszynska feels a change of pace is mandatory: “We either work towards integrating soil ecosystems within a larger picture of a controlled and awareness-based de-growth, or we are likely to face a catastrophic version of it”.

Takeaways for AI4SoilHealth

The conversation with Anna Krzywoszynska has inspired several reflections at the project level, starting from the need to keep AI-supported environmental monitoring grounded in soil health principles.

As a data-driven research project, AI4SoilHealth should integrate insights offered by social sciences, environmental humanities, and eco-philosophy disciplines to ensure research supports land workers and avoids becoming isolated in a theoretical bubble of data. The project aims to leverage AI to empower farmers and land managers, fostering collaborative efforts in soil care practices and solutions that recognize and protect soil’s ‘agency’.

AI4SoilHealth recognises the importance of fostering a dialogue between science and society as the cornerstone for developing policy recommendations that respond to the needs of a sustainable global economy and society. **The potential for AI in environmental monitoring is immense, yet it's crucial for this technology to account for human-land relations and address the needs of the wider natural world.**

Annex 1 Interview protocol

GENERAL INFORMATION
• Name • Surname • Contact e-mail • Institution/organisation • Professional profile • Main policy areas • In case you are involved in a European-funded project, please provide the project's hyperlink or full name below.
Soil Health – Current and future policies
Q1 What are the key soil health-related policy goal(s) in your area of expertise?
• *Overarching goals* • *Do you use Targets, what are they?* • *What is the time horizon (if available)* • *What are the territorial scope and policy references (e.g., global, EU, SDGs, Aaichi targets)*
Q2 Which legislation or policy interventions are currently in use, or under consideration, to help achieve the goal(s) you previously identified regarding soil health?
Legislative: • *Water framework,* • *Biodiversity,* • *Climate,* • *Agriculture,* • *Environment* Other:
Q3 Under what framework would you normally think of soils?
Conceptual framework to link to policy: • *DPSIR,* • *Ecosystem services,* • *Natural Resources* • *Natural capital,* • *Economic or green accounting.* Other:

Q4 To the best of your knowledge, are you aware of any activities or legislation within your policy domain that is causing damage or unintended consequences to soil health? How could this be addressed?
Q5 Assuming favorable circumstances, what are your expectations for the development of soil health over the next 20 years? Which specific metrics or measurements would you prefer to use to monitor and demonstrate successful outcomes for your policy area?
Soil Health – Technical considerations in support of policy
Q6 What type of soil information do you need to inform your policy objectives?
• *Maps,* • *Monitoring of change*
Q7 At what spatial scale do you need information to support your policy efforts?
• *Farm scale* • *Landscape scale* • *Regional scale* • *National scale* • *Pan European scale* • *Global scale*
Q8 What is your preferred interpretive or reporting unit to assess your policy goals?
• *Habitats or land cover (forest, farmland, grassland, etc)* • *Soil types /series* • *Soil properties (add example ph/texture* • *Farm types (arable, pastoral, dairy, etc.)* • *Soil management systems used (example..)* • *Administrative boundaries* Other:
Q9 How often does data need to be updated to ensure you can meet your policy objectives and reporting?
• *Yearly* • *5 yearly* • *10 yearly* Other:
Q10 To what extent are climate change and land use changes currently considered in the development of soil health interventions/measures?
Q11 Do you have any problems accessing the soil health information you need? If so, what are the constraints?
• *Data is unavailable*

• *Wrong resolution* • *IPR or licensing restraints* Other:	
Q12 **Accuracy and precision:** In your opinion, what degree or range of accuracy and precision is preferable? Why?	
e.g., 2% change over 10 years	
AI4Soil Health – What can the AI4SoilHealth project do for you?	
Q13 From your perspective, what are the essential activities that **healthy soils** need to perform in order for your policy goals and interventions to be considered successful?	
• *Production of food* • *Production of fibre & biofuels, timber* • *Water purification & retention* • *Carbon Sequestration* • *Habitat for biodiversity* • *Recycling of nutrients & Agrochemical* Other:	
Q14 To your knowledge, are the above **soil quality aspects** currently measured or assessed at the EU level?	
• *Yes* • *No* • *Name a source as an example:*	
Q15 What **change** in soil health monitoring systems might help you achieve your policy goals?	
• *Provide greater spatial resolution/scale* • *Summary of error values/uncertainty* • *Change the frequency of data and reporting* • *Increase depth of observations* Other:	
Q16 How will new information help you in your job or role?	

References

de Sadeleer, N. 2023. Environmental Law in the EU: A Pathway Toward the Green Transition. In: Garcia, M.d.G., Cortês, A. (eds) Blue Planet Law. Sustainable Development Goals Series. Springer, Cham. https://doi.org/10.1007/978-3-031-24888-7_2

Dr. Hannes Böttcher Carina Zell-Ziegler Anke Herold Anne Siemons EU LULUCF Regulation explained Summary of core provisions and expected effects https://www.oeko.de/fileadmin/oekodoc/Analysis-of-LULUCF-Regulation.pdf

EC 2020c, Communication from the Commission, 'Chemicals strategy for sustainability 'Towards a toxic-free environment', COM/2020/667 final

EC 2021, Staff Working Document Accompanying the document Communication from the Commission EU Soil Strategy for 2030 Reaping the benefits of healthy soils for people, food, nature and climate (SWD/2021/323 final)

EC 2021b Communication from the Commission 'New EU forest strategy for 2030', COM/2021/572 final.

EC 2023, Directorate-General for Research and Innovation, Janssen, M., Schiele, J., 'Study supporting the assessment of EU missions and the review of mission areas – Mission A Soil Deal for Europe assessment report', Publications Office of the European Union, 2023

EC Staff Working document impact assessment report Accompanying the proposal for a Directive of the European Parliament and of the Council on Soil Monitoring and Resilience (Soil Monitoring Law) SWD/2023/417 final

EC, 2019, Communication from the Commission 'The European Green Deal' COM/2019/640 final

EC, 2020 Directorate-General for Research and Innovation, Veerman, C., Pinto Correia, T., Bastioli, C. et al., 'Caring for soil is caring for life – Ensure 75% of soils are healthy by 2030 for food, people, nature and climate – Report of the Mission board for Soil health and food', Publications Office, 2020,

EC, 2020, Communication from the Commission ' A new Circular Economy Action Plan For a cleaner and more competitive Europe' COM/2020/98 final

EC, 2020e, Communication from the Commission 'EU Biodiversity Strategy for 2030: bringing nature back into our lives' COM/2020/380 final

EC, 2020f, Communication from the Commission 'A Farm to Fork Strategy for a fair, healthy and environmentally-friendly food system' COM/2020/381 final

EC, 2021, Communication from the Commission ‘Forging a climate-resilient Europe - the new EU Strategy on Adaptation to Climate Change’ COM/2021/82 final

EC, 2021, Communication from the Commission ‘Sustainable Carbon Cycles’ COM(2021) 800 final

EC, 2021, Communication from the Commission 'An action plan for the development of organic production' COM(2021)141 final

EC, 2021c, Communication from the Commission ‘Fit for 55»: Delivering the EU’s 2030 Climate Target on the way to climate neutrality’ COM/2021/550 final

EC, 2021e, Communication from the Commission 'EU Soil Strategy for 2030: reaping the benefits of healthy soils for people, food, nature and culture' COM/2021/699 final

EC, 2021e, Communication from the Commission 'EU Soil Strategy for 2030: reaping the benefits of healthy soils for people, food, nature and culture' COM/2021/699 final

EC, 2022 ‘Communication from the Commission on European missions’ (COM(2021) 609 final)

EC, 2022 Proposal from the Commission for a Regulation establishing a Union certification framework for carbon removals, COM/2022/672 final

EC, 2022, Proposal for a regulation on the sustainable use of plant protection products, COM/2022/305 final

EC, 2022, Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on nature restoration, COM/2022/304 final

EEA, 2019c. *The European environment - state and outlook 2020*.

EEA, 2022 “Soil monitoring in Europe — Indicators and thresholds for soil health assessments” Report No 08/2022

EU, 2007, Directive (EU) 2007/2 establishing an Infrastructure for Spatial Information in the European Community (INSPIRE) (OJ L 108, 25.4.2007, p. 1–14)

EU, 2018a, Regulation (EU) No 2018/841 on the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry in the 2030 climate and energy framework (OJ L 156, 19.6.2018,).

EU, 2021, Regulation (EU) No 2021/1119 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law') (*OJ L 243, 9.7.2021*)

EU, 2023 Regulation (EU) No 2023/1115 on the making available on the Union market and the export from the Union of certain commodities and products associated with deforestation and forest degradation and repealing Regulation (EU) No 995/2010 (*OJ L 150, 9.6.2023, p. 206–24)*

European Commission, Directorate-General for Research and Innovation, Kubeczko, K., Bernstein, M., Wasserbacher, D. et al., *S&T&I for 2050 – Science, technology and innovation for ecosystem performance – Accelerating sustainability transitions*, Publications Office of the European Union, 2023, **https://data.europa.eu/doi/10.2777/100029**

Heuser, I 2022 Soil Governance in current European Union Law and in the European Green Deal,

Revision of the Industrial Emissions Directive, Legislative Observatory (OEIL), European Parliament https://www.europarl.europa.eu/RegData/etudes/BRIE/2022/733570/EPRS_BRI(2022)733570_EN.pdf

Soil Security, Volume 6, 2022, 100053, ISSN 26670062, https://doi.org/10.1016/j.soisec.2022.100053.