European Commission

Joint Research Centre

Changes in soil health in the EU

An assessment of the changes in policy, data availability, monitoring, literacy and indicators over the past decades

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2026



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JRC143225
EUR 40788

PDF ISBN 978-92-68-42065-2 ISSN 1831-9424 doi:10.2760/1968092 KJ-01-26-313-EN-N

Luxembourg: Publications Office of the European Union, 2026

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How to cite this report: Broothaerts, N., Efthimiou, N., Fendrich, A., Jones, A. and Panagos, P., *Changes in soil health in the EU - An assessment of the changes in policy, data availability, monitoring, literacy and indicators over the past decades*, Publications Office of the European Union, Luxembourg, 2026, https://data.europa.eu/doi/10.2760/1968092, JRC143225.

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Abstract

Healthy soils are essential for our environment and society, as they deliver crucial ecosystem services. This report provides an assessment of the changes in soil governance, soil data systems, soil monitoring frameworks, soil literacy, and soil degradation indicators in the EU over the past decades. The report shows that EU soil governance has evolved from fragmented and largely sectoral approaches towards an integrated soil health framework increasingly supported by harmonised monitoring systems, interoperable data infrastructures, and common policy objectives. Milestones for soil protection in the EU were the entry into force of the Soil Monitoring and Resilience Directive, the Mission Soil, the EU Soil Strategy for 2030, and the soil-related objectives under the Common Agricultural Policy. The report shows that future soil governance should combine harmonised monitoring, FAIR data principles, technological innovation, and improved soil literacy within an integrated EU soil knowledge ecosystem. Such an approach would strengthen soil policy implementation, accelerate the implementation of sustainable soil management practices, and bring all soil degradation indicators on track to reach healthy soils by 2050.

Acknowledgements

This report was jointly realised by the EUSO Project under the JRC's Institutional Work Programme 2025-2027 and the Administrative Agreement JRC No 36283-2022 (Implementation of the soil monitoring tasks of the Mission Soil). Leonidas Liakos and Christopher Havenga are thanked for the graphical support.

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Executive summary

Policy context

Healthy soils are essential for our environment and society, as they deliver crucial ecosystem services. This report supports the implementation of the EU Soil Strategy for 2030, the Horizon Europe Mission 'A Soil Deal for Europe' (Mission Soil), the Soil Monitoring and Resilience Directive (SMRD), and soil-related objectives under the Common Agricultural Policy (CAP). It examines how soil governance, soil data systems, monitoring frameworks, soil literacy, and soil degradation indicators have changed in the EU over the past decades. The report was prepared to support policymakers, researchers, and practitioners involved in soil protection and sustainable land management. The findings are relevant to the ongoing development of harmonised EU soil monitoring and reporting systems and to broader climate, biodiversity, water, and land-use policies.

Key conclusions

The report shows that European soil governance has evolved from fragmented and largely sectoral approaches towards an integrated soil health framework increasingly supported by harmonised monitoring systems, interoperable data infrastructures, and common policy objectives. The EU Soil Strategy for 2030, the Mission Soil, and the SMRD represent major steps towards a more coherent and evidence-based approach to soil protection and restoration.

One of the main conclusions is that effective soil governance depends on reliable, accessible, and interoperable soil data. Significant progress has been achieved through initiatives such as the European Soil Data Centre (ESDAC), the EU Soil Observatory (EUSO), and LUCAS Soil. However, important challenges remain, including fragmented datasets, methodological inconsistencies, uneven monitoring capacities among Member States, and barriers to data sharing and reuse.

The report confirms the need for harmonised soil monitoring systems capable of integrating field observations, earth observation, modelling, and sensing technologies. It highlights the growing role of artificial intelligence, cloud computing, and big data approaches in supporting soil assessment and decision-making. Future monitoring systems will require common indicators and flexible architectures capable of accommodating diverse environmental and policy contexts.

The analysis also identifies soil literacy as a critical enabling factor. Investments in monitoring and data infrastructures will have limited impact unless farmers, land managers, advisors, policymakers, and citizens can understand and use soil information effectively. Strengthening awareness, education, and stakeholder engagement is therefore essential for translating knowledge into action.

Furthermore, quantitative, EU-wide trends for seven soil degradation indicators suggest that three indicators improved over the past decades (soil erosion by water, harvest erosion, and phosphorus deficiency). Conversely, results suggest that three indicators deteriorated over the past decades (loss of soil organic carbon, phosphorus excess and soil sealing). Projections towards 2050 suggest that four indicators will deteriorate in the upcoming decades due to climate change, continued unsustainable management practices and urbanisation.

The report concludes that future soil governance should combine harmonised monitoring, FAIR data principles, technological innovation, and improved soil literacy within an integrated European soil knowledge ecosystem. Such an approach would strengthen policy implementation, reduce uncertainties, and support the EU objective of achieving healthy soils by 2050.

Main findings

Three phases in European soil policy were identified over the last decades: a legacy period based on fragmented datasets and sectoral policies; a harmonisation phase characterised by the development of common data infrastructures and monitoring frameworks; and a current phase centred on soil health, integrated monitoring, and evidence-based governance.

Soil data systems have evolved from static soil surveys and maps towards interoperable platforms integrating field observations, earth observation, sensing technologies, digital soil mapping and modelling. This evolution has substantially improved the spatial and temporal resolution of soil information, enabled more accurate assessments of soil condition, trends, and ecosystem functions while supporting evidence-based decision-making. Major advances have been achieved through ESDAC and Mission Soil initiatives.

Despite substantial progress, data fragmentation, inconsistent methodologies, limited interoperability, and uneven monitoring capacities continue to hinder comprehensive soil assessments across Europe. Differences in sampling protocols, indicator selection and data quality standards among Member States further complicate the harmonization and comparability of soil information at the EU scale. Long-term sustainability of data infrastructures and monitoring networks remains a concern, requiring sustained investment, institutional coordination, and long-term policy commitment to ensure the continuity and accessibility of high-quality soil data.

Soil literacy is increasingly recognised as a prerequisite for effective soil governance. Improved understanding of soil functions, threats, and management options among stakeholders enhances the uptake of monitoring results and supports evidence-based decision-making.

Quantitative trends for seven soil degradation indicators show that three indicators improved, and three indicators deteriorated over the past decades, highlighting the importance of a continued investment in soil monitoring and related research, to accelerate the implementation of sustainable soil management practices and to bring all indicators on track to reach healthy soils by 2050.

Related and future Joint Research Centre work

The EU Soil Observatory (EUSO) of the Joint Research Centre (JRC) provides knowledge and data on soils to underpin EU soil policy development and implementation. Future work of the JRC will include supporting the implementation of the SMRD and the Mission Soil and providing scientific evidence and recommendations for soil health monitoring and sustainable soil management practices.

Quick guide

Healthy soils are essential for food production, climate regulation, biodiversity, and ecosystem resilience. This report reviews how European soil governance, monitoring systems, data infrastructures, and soil literacy initiatives have evolved to support these functions.

Chapter 1 provides a general introduction in the topic. Chapter 2 discusses transformations in soil policies over the past decades. Chapter 3 provides an overview of the changes in soil data availability. Chapter 4 analyses the evolution of soil monitoring. Chapter 5 provides an overview of the changes in soil literacy and societal engagement. Finally, Chapter 6 discusses quantitative trends for seven soil degradation indicators. The report highlights both progress and remaining challenges, particularly regarding data interoperability, harmonised monitoring, and stakeholder engagement. Its findings support ongoing efforts to establish a coherent European framework for soil monitoring, assessment, and sustainable soil management.

1. Introduction

Soils are among the most valuable natural resources on Earth, providing essential ecosystem functions and services that underpin human well-being, economic development, and environmental sustainability. They support food, fibre, and biomass production, regulate water flows and nutrient cycling, store and filter pollutants, host a large proportion of terrestrial biodiversity, and represent one of the largest carbon reservoirs in the biosphere. Healthy soils are therefore fundamental for achieving multiple societal objectives, including food security, climate change mitigation and adaptation, biodiversity conservation, water quality protection, and sustainable land management.

Despite their importance, soils across Europe and globally are under increasing pressure from a wide range of degradation processes (Arias-Navarro et al. 2024). Soil erosion, organic matter decline, compaction, contamination, salinisation, biodiversity loss, sealing, and desertification continue to affect soil functions and reduce the capacity of soils to deliver ecosystem services. These pressures are often exacerbated by unsustainable land management practices, land-use change, urbanisation, climate change, and increasing demands on natural resources. The consequences extend beyond the soil system itself, influencing agricultural productivity, water availability and quality, greenhouse gas emissions, ecosystem resilience, and human health.

Growing recognition of these challenges has contributed to the emergence of the concept of soil health, which has increasingly become the central framework for soil policy and management. Soil health[1] emphasizes the capacity of soil to function as a living ecosystem that sustains plants, animals, and humans while maintaining its ecological integrity and resilience. Unlike traditional approaches focused primarily on individual soil properties or degradation processes, the soil health concept promotes a more integrated assessment of soil condition, encompassing physical, chemical, and biological dimensions as well as the multiple functions and services that soils provide.

Over the past two decades, soil protection has gained increasing prominence within the European policy agenda. A major milestone was the adoption of the EU Soil Strategy for 2030, which established a long-term vision for achieving healthy soils across the European Union by 2050 and identified soil health as a prerequisite for climate neutrality, biodiversity restoration, sustainable food systems, and a circular bioeconomy. The Strategy places particular emphasis on improving soil monitoring, strengthening knowledge and data infrastructures, promoting sustainable soil management, and enhancing public awareness of the importance of soils.

These ambitions are further supported by the Horizon Europe Mission 'A Soil Deal for Europe' (Mission Soil), which seeks to accelerate the transition towards healthy soils through research and innovation, Living Labs and Lighthouses, stakeholder engagement, and the development of practical solutions for soil restoration and sustainable management. In parallel, the Soil Monitoring and Resilience Directive (SMRD) represents an important step towards establishing a harmonised framework for soil monitoring and assessment across Member States (MS). The Directive aims to improve the availability, comparability, and accessibility of soil information, while providing a common basis for assessing soil condition and supporting evidence-based policy implementation. Soil protection objectives are also increasingly embedded within sectoral policies, particularly the

1 The Soil Monitoring Law defines heathy soils as: 'Healthy soils are soils that are in good chemical, biological and physical condition and which can therefore provide ecosystem services vital to humans and the environment, such as safe, nutritious and sufficient food, biomass, clean water, nutrients cycling, carbon storage and a habitat for biodiversity'

Common Agricultural Policy (CAP), which promotes sustainable agricultural practices through conditionality requirements, eco-schemes, and agri-environmental measures. Moreover, the Carbon Removals and Carbon Farming (CRCF) Regulation establishes harmonised standards for the certification of carbon removals and emission reductions by defining common quality criteria, monitoring, reporting, and verification (MRV) requirements, together with independent third-party certification procedures. These provisions are intended to ensure the environmental integrity, transparency, and comparability of certified removal and emission-reduction activities across EU MS.

Collectively, these initiatives underscore that effective soil governance increasingly relies on robust monitoring systems, interoperable data infrastructures, and scientific tools capable of providing timely, harmonised, and policy-relevant soil information. In recent years, major advances have been achieved in soil monitoring, earth observation, digital soil mapping, sensing technologies, artificial intelligence, and data management. At the same time, increasing attention has been devoted to soil literacy and stakeholder engagement, recognising that sustainable soil management requires not only better data and technologies but also greater awareness and understanding among policymakers, land managers, practitioners, and citizens.

Against this background, the present report provides a comprehensive assessment of the scientific, technical, and policy foundations required to support the transition towards healthy soils in Europe. The report examines the evolution of soil governance frameworks, soil data systems, monitoring approaches, and soil literacy initiatives over the past decades (from approximately the mid-1980s to the present), while identifying current challenges, emerging opportunities, and future priorities. Particular attention is given to the role of harmonised monitoring systems, FAIR data principles, technological innovation, and integrated knowledge ecosystems in supporting evidence-based soil governance.

The report is structured into five thematic chapters. Following this introduction, **Chapter 2** reviews the evolution of soil governance in Europe, examining major policy developments and the emergence of soil health as a central policy objective. **Chapter 3** focuses on soil data systems and information infrastructures, discussing data availability, accessibility, harmonisation, interoperability, and the growing role of digital technologies and FAIR data principles. **Chapter 4** examines soil monitoring systems, indicators, and assessment frameworks, including advances in earth observation, digital soil mapping, sensing technologies, modelling approaches, and soil health assessment. **Chapter 5** addresses soil literacy, stakeholder engagement, and knowledge transfer mechanisms, highlighting their importance for effective policy implementation and behavioural change. Finally, **Chapter 6** provides EU-wide, quantitative trends for seven soil degradation indicators over the past decades and projections towards 2050.

Taken together, the report illustrates how soil governance is evolving from fragmented and largely sectoral approaches towards integrated soil health systems that combine policy, monitoring, data, technology, and societal engagement. This transition is essential for addressing the complex challenges facing European soils and for ensuring that soils continue to provide the ecosystem functions and services upon which society depends.

2. Changes in EU soil policies

2.1. Introduction

In Europe, almost 12 million ha of soil are being degraded each year (Rossi 2020), corresponding to a loss of about 23 ha per minute. Currently, an estimated 60–70% of soils in the EU are considered unhealthy, primarily because of unsustainable management practices (Panagos et al., 2024b). Soil degradation is not only an environmental crisis but also a profound socioeconomic challenge. Declining productivity undermines rural livelihoods, intensifies food (Montanarella and Panagos 2021a) and water insecurity, and weakens local and regional economies.

Reversing these trends requires sustained and coherent policy action. Over the past decades, the EU has progressively developed an array of policy instruments addressing soil protection and restoration, ranging from the early integration of soil concerns into agricultural and environmental frameworks to the landmark adoption of the SMRD. Previous work has provided important overviews of the EU policy landscape relevant to soil, including analyses of soil priorities embedded within the European Green Deal (Montanarella and Panagos 2021b) and broader assessments of how EU instruments address soil health across multiple domains (Panagos et al. 2022a).

Nonetheless, an extensive and systematic review of the full trajectory of EU soil policy – tracing how governance frameworks have evolved, interacted, and transformed over time – remains largely absent from the literature. Filling this gap is the central objective of the present chapter. It should be noted that parallel efforts have been made at the national level, with several MS developing dedicated soil protection laws and monitoring frameworks independently of EU-level action (e.g. Germany, the Netherlands, Austria); however, a review of national soil policies falls outside the scope of this chapter, which focuses exclusively on EU-level instruments and their governance logic.

This chapter is structured as follows. Section 2.2 maps the full landscape of EU policies with direct or indirect relevance to soil, including agricultural frameworks, environmental strategies, research and innovation (R&I) programmes, and global governance linkages. This section also examines synergies and trade-offs that arise when soil-related management objectives intersect across different policy domains. Section 2.3 situates these instruments within a chronological narrative of three distinct governance phases – from pre-2006 regulatory fragmentation, through the failed legislative attempt and institutional learning of 2006–2019, to the accelerated integration of soil governance under the European Green Deal after 2019 and the introduction of the SMRD. The chapter closes with Section 2.4, which outlines the outlook and future perspectives for EU soil governance considering intensifying environmental pressures, emerging regulatory instruments, and the systemic transitions underway.

2.2. Major soil-related policy frameworks in the EU

The present section provides an overview of the soil-related policy landscape at the EU level; national soil protection legislation developed independently by MS falls outside the scope of this review. The major frameworks addressed here include the EU Thematic Strategy for Soil Protection (STS), the Common Agricultural Policy (CAP) and its successive reform cycles, the suite of the European Green Deal strategies – namely the Biodiversity Strategy for 2030, the Farm to Fork Strategy (F2F), the Zero Pollution Action Plan (ZPAP), the Forests Strategy for 2030, and the European Climate Law – the Carbon Removals and Carbon Farming (CRCF) Regulation, the Mission Soil, and the Soil Monitoring and Resilience Directive (SMRD) which represents the most recent and

most consequential legislative milestone in EU soil governance. These instruments reflect the gradual maturation of soil governance from fragmented sectoral provisions towards an integrated regulatory framework. While all major frameworks are covered, the treatment is necessarily selective in depth on specific initiatives, given their centrality to the current EU soil governance architecture. Readers seeking more detailed information on individual instruments are encouraged to consult the references and official documentation links provided alongside each entry.

2.2.1. The Common Agricultural Policy (CAP)

The Common Agricultural Policy (CAP) serves as the central policy framework guiding agricultural production, rural development, and resource management across the EU. In 2000, the Agenda 2000 reform package introduced the CAP's two-pillar structure, distinguishing direct payments to farmers and market support measures (Pillar I) from rural development (Pillar II).

This reform formally integrated rural development into the CAP, supporting sustainable agricultural practices and territorial development through multiannual, co-financed[2] initiatives known as Rural Development Programmes (RDPs). RDPs precede the cross-compliance measures and have played a significant role in promoting soil protection by financing agri-environment-climate initiatives, support for areas facing natural constraints, organic farming, afforestation, erosion control, and sustainable land management practices (Barbayiannis et al. 2011), thereby contributing directly to soil conservation, climate change mitigation and adaptation, and broader environmental objectives of the CAP.

Since 2000, rural development has been implemented through successive multiannual programming periods (e.g. 2000–2006, 2007–2013, 2014–2020, 2023–2027). The 2000–2006 Programme included 17 agri-environmental indicators (AEIs) promoting practices that benefited soil health, such as organic farming, extensive livestock systems, reduction of water nitrification, and conservation of landscape features like stone walls (Gobin et al. 2004; Yli-Viikari et al. 2007). In the 2007–2013 Programme, one of the main axes focused on the 'Improvement of the Environment and the Countryside', supporting soil-protective measures including crop rotation, erosion control, and sustainable land management (https://agriculture.ec.europa.eu/cap-my-country/rural-development/previous-rdp-periods_en). The 2014–2020 programming period further strengthened the environmental dimension of rural development, with measures supporting ecosystem restoration, sustainable land management, and climate action (https://agriculture.ec.europa.eu/cap-my-country/rural-development_en). In the current 2023–2027 CAP Strategic Plans, at least 35 % of rural development funding is allocated for environmental and climate objectives, including soil conservation, land restoration, and adoption of sustainable farming practices (https://agriculture.ec.europa.eu/common-agricultural-policy/cap-overview_en).

The 2003 reform – often referred to as the 'Mid-term Review' of the CAP – promoted an eco-friendlier production model (Fellmann et al. 2025). The novel cross-compliance mechanism linked farmers' eligibility for financial support not only to productivity but also to the adoption of climate- and nature-sensitive practices (Barbayiannis et al. 2011; Panagos et al. 2020). This shift toward conservation agriculture led to the establishment of the Good Agricultural and Environmental Conditions (GAEC) standards (MARS 2014), which MS implement through national and regional

2 By the European Agricultural Fund for Rural Development and MS.

policies (Louwagie et al. 2011). For example, GAEC 4-7a[3] are particularly relevant to soil erosion prevention. Their enforcement reduced soil loss from EU croplands by approximately 20 %, and by an average of 9.5 % across all agricultural land between 2000 and 2010 (see e.g. chapter 6 and Panagos et al. 2015b).

The 2014–2020 reform reinforced environmental integration through the introduction of mandatory 'greening' measures under Pillar I, linking a share of direct payments to environmentally beneficial practices such as crop diversification, maintenance of permanent grasslands, and the establishment of Ecological Focus Areas (Panagos et al. 2020). These requirements enhanced landscape heterogeneity, reduced soil disturbance, and contributed indirectly to erosion control and soil organic matter conservation. At the same time, under Pillar II (RDPs), soil erosion prevention and sustainable soil management (FAO 2017) were explicitly prioritized through agri-environment-climate measures, support for conservation agriculture, and land management practices aimed at maintaining soil structure and fertility.

Environmental and climate resilience actions are at the forefront of the reformed 2023–2027 CAP (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=SWD%3A2018%3A301%3AFIN, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2018%3A392%3AFIN). Within the new performance monitoring framework, the percentage of agricultural area affected by severe soil erosion is included among the AEIs used to assess the CAP's contribution to reducing soil loss bellow critical thresholds[4], thereby preventing long-term and potentially irreversible[5] soil degradation. Under the new CAP Strategic Plans, MS are required to design management interventions aimed at reducing erosion risk, while farmers receive financial support conditional upon compliance with strengthened environmental standards. The previous cross-compliance and greening mechanisms have been integrated into a system of enhanced conditionality, structured around the nine GAEC standards. Collectively, these standards aim to strengthen soil conservation, biodiversity protection, and climate mitigation compared to the 2014–2020 framework. Furthermore, the post-2020 CAP introduces targeted interventions to enhance SOC in agricultural soils and to preserve wetlands and restore drained peatlands, recognising their critical role as

3 GAEC 4: minimum soil cover (crop rotation, winter cover crops, crop residues, mulching, GAEC 5: minimizing soil erosion, GAEC 6: maintaining the level of organic matter in soil, GAEC 7a: setting boundaries (stone walls, strip cropping, buffer strips).

4 E.g. evaluating the severity of erosion requires defining a threshold that distinguishes tolerable from intolerable soil loss (FAO 2019). Ideally, soil loss would remain at or below the rate at which new soil is naturally formed (Morgan 2005). This is not the case in the EU, where average soil displacement by water exceeds the soil formation rate by about 1.6% (Panagos et al. 2015a, 2016). In the context of sustainable soil management soil loss is acceptable when ecosystem services are maintained without compromising its sustainability. In croplands, soil loss tolerance refers to the maximum erosion rate that still allows soil fertility to be maintained over periods of roughly 20–25 years (McCormack and Young 1981). An average annual loss of about 11 t ha-1 is commonly considered tolerable (Hall et al. 1979; Parris 1999), much lower thresholds, down to 2 t ha-1, are recommended for shallow or highly erosion-prone soils (Hudson 1988).

5 Soils are categorised as reversibly or non-reversibly degraded based on the intensity of the soil degradation process and their potential for restoration (Lal 1997; 2001). For example, soil erosion is considered reversible when i) topsoil loss is moderate and enough soil depth remains to allow vegetation recovery, ii) vegetation cover decline has not exceeded ecological thresholds, and iii) surface crusting, compaction, or rill formation can still be remedied. Conversely, erosion is deemed non-reversible when i) complete soil horizons have been lost, exposing bedrock or nutrient-poor subsoil, ii) soil depth is critically low, severely limiting water retention and preventing vegetation recovery, and iii) severe gullies or mass-wasting features have developed.

carbon sinks contributing to climate change mitigation (CAP Impact Indicator[6] I.11 – SOC in agricultural soils).

2.2.2. The Thematic Strategy for Soil Protection (STS)

In 2006, the European Commission (EC) adopted the Thematic Strategy for Soil Protection (STS), the first comprehensive EU framework dedicated to soil protection. The Strategy identified eight major threats to soil, including erosion, organic matter decline, contamination, compaction, salinization, soil sealing, landslides, and biodiversity loss, and emphasized their potential impacts on food security, ecosystem services, and environmental sustainability. Its objectives were to i) integrate soil protection into EU and national policies, ii) raise societal awareness of the crucial role of soils, and iii) stimulate research on soil degradation and management (Ronchi et al. 2019). The STS consisted of a Communication from the EC, a proposal for a for a European law namely Soil Framework Directive, and an Impact Assessment. At the time, 42 M ha of European land were estimated to be affected by soil degradation, mainly due to erosion.

Despite its ambitions, the proposed Directive failed to achieve majority support in the Council, with five MS (the UK, Germany, Austria, France, and the Netherlands) blocking it, citing concerns over national sovereignty and the transboundary implications of soil governance (Chen 2020; Montanarella and Panagos 2021a). As a result, the legislative pillar of the STS was withdrawn in 2014, leaving the Strategy as a non-binding policy framework.

The withdrawal removed the proposed Soil Framework Directive from the legislative agenda after eight years of deadlock in the Council. Following this withdrawal, soil protection continued through integration into existing sectoral policies rather than through a dedicated horizontal directive. This marked a transition from an attempted binding legislative framework toward incremental policy integration across agriculture, climate, biodiversity, and research instruments.

The STS laid the conceptual groundwork for EU soil protection policies and has had a lasting influence on agricultural and environmental governance. Its objectives were gradually integrated into multiple EU instruments, including the CAP through GAEC standards, cross-compliance, RDPs, and later greening and eco-scheme measures. Beyond the CAP, the STS influenced the EU Soil Strategy for 2030, soil monitoring and research frameworks (JRC, Horizon Europe), and alignment with international frameworks such as the United Nations Convention to Combat Desertification (UNCCD) and SDGs. **Table 1** summarizes the main spillovers of the STS into EU soil-related policies, illustrated in **Figure 1**.

Table 1. Major spillovers of the 2006 Soil Thematic Strategy (STS) into EU soil-related policies, CAP instruments, and broader governance initiatives.

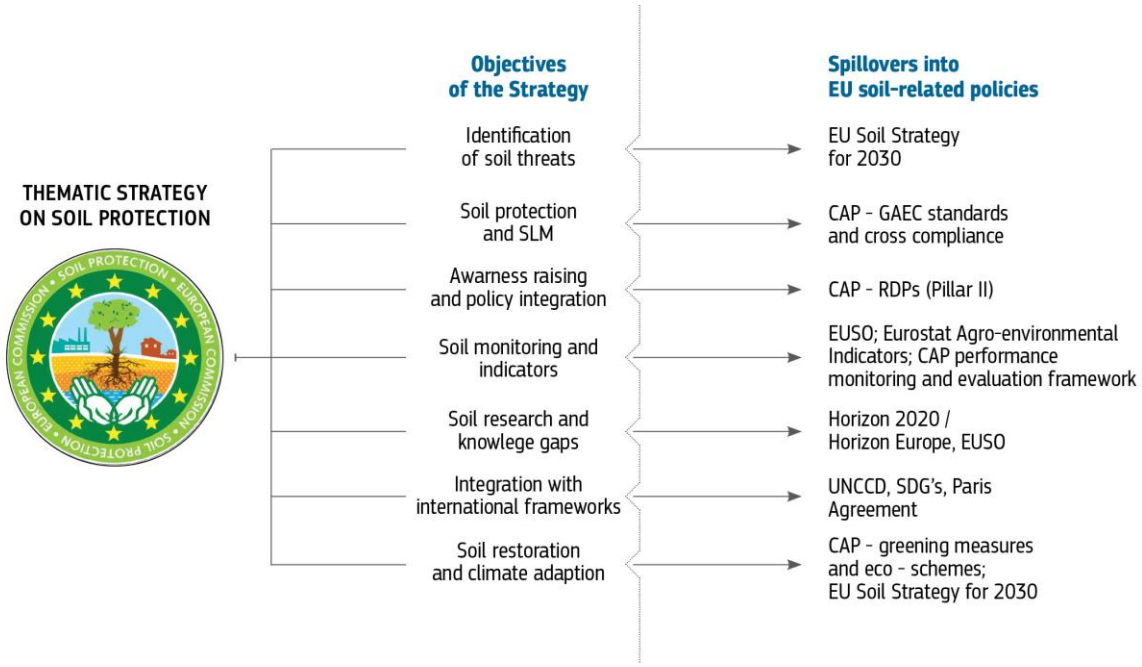
STS Element / Objective	Policy / Instrument Influenced	Type of Influence / Spillover	Notes
Identification of soil threats (erosion, SOM decline, sealing, contamination,	Soil Strategy for 2030	Conceptual foundation; extended threat list; monitoring focus	Provides the scientific and policy rationale for soil protection targets

6 A quantitative measure used to assess the long-term environmental, economic, or social effects of CAP interventions, beyond immediate outputs, and to determine whether the policy is achieving its strategic objectives.

STS Element / Objective	Policy / Instrument Influenced	Type of Influence / Spillover	Notes
compaction, salinization, landslides, biodiversity loss)			
Soil protection and sustainable management	CAP – GAEC standards & cross-compliance	Operationalisation via mandatory environmental standards	GAEC 1–9 and cross-compliance measures directly target erosion, soil cover, crop rotation, permanent grassland protection
Awareness raising and policy integration	CAP – RDPs (Pillar II)	Agri-environment-climate measures; rural development funding for soil conservation	Soil-specific AEIs, erosion control, SOC enhancement, sustainable land management
Soil monitoring and indicators	EU Soil Observatory (JRC) / Eurostat Agri-environmental Indicators; CAP performance monitoring and evaluation framework (PMEF)	Provided methodological basis for monitoring erosion, SOC, and land degradation	Indicators used in CAP Strategic Plans and EU Soil Strategy for 2030
Soil research and knowledge gaps	Horizon 2020 / Horizon Europe, Mission Soil, EU Soil Observatory	Directed funding toward soil research and demonstration projects	Builds on STS call for increased research and knowledge dissemination
Integration with international frameworks	UNCCD, SDGs, Paris Agreement	Alignment of EU soil policy with global soil, climate, and land degradation targets	Supports “no net land take,” carbon storage, and resilience objectives
Soil restoration and climate adaptation	CAP – greening measures and eco-schemes; EU Soil Strategy for 2030	Financial incentives for SOC increase, buffer strips, wetland and peatland restoration	Ensures measurable soil health objectives in CAP and Green Deal policies

Source: JRC analysis.

Figure 1. The 2006 Soil Thematic Strategy (STS) objectives and major spillovers into EU soil-related policies.



Source: JRC analysis.

2.2.3. The Roadmap to a Resource-Efficient Europe

The Roadmap to a Resource-Efficient Europe marked an important step in integrating soil and land considerations into the EU's broader resource-efficiency agenda. Although not a dedicated soil policy, it recognized land and soil as finite natural resources and introduced the objective of achieving "no net land take[7] by 2050." By linking soil sealing, land degradation, and ecosystem services to long-term economic sustainability, the Roadmap contributed to strengthening the policy rationale for subsequent initiatives on soil health, including the EU Soil Strategy for 2030 and related European Green Deal measures.

2.2.4. Environmental Action Programmes

Environmental Action Programmes (EAPs) are long-term strategic frameworks that guide environmental policy and action across MS. EAPs set priority objectives, targets, and guiding principles for a defined period (usually 7–10 years). They shape legislation, funding priorities, and policy integration in areas such as climate change, biodiversity, pollution control, and resource efficiency. Since the 1970s, successive EAPs have played a central role in embedding environmental protection into EU governance, and since 2002 with a specific focus on soil protection.

7 According to the SMRD (Article 3; Definition No. 17) Land take is the conversion of natural and semi-natural land into artificial land. Therefore, 'no net land take' can be interpreted as ensuring that the overall area of artificial land does not increase over time, with new land development being compensated by the restoration or re-naturalisation of previously developed land.

— The 6th EAP (2002–2012) was the EU's overarching environmental policy framework for a decade, adopted under Decision No 1600/2002/EC. It structured EU environmental priorities around four thematic areas: climate change, nature and biodiversity, environment and health, and natural resources and waste. Crucially for soil governance, the 6th EAP explicitly recognized soil degradation as a serious environmental challenge and called for a thematic strategy on soil protection – directly leading to the 2006 STS. In that sense, it marked the first time soil was elevated from a largely sectoral concern to a strategic EU-level environmental priority.

— The 7th EAP titled 'Living well, within the limits of our planet' (Decision No 1386/2013/EU), covering the period 2014–2020, established the objective of protecting, conserving and enhancing the Union's natural capital, explicitly referencing soil protection and sustainable land management. It called for progress toward addressing land degradation and reducing land take.

— Its successor, the 8th EAP (Decision (EU) 2022/591), covering 2021–2030, provides the legal framework for implementing the European Green Deal. It reinforces commitments to climate neutrality, zero pollution, biodiversity protection, and sustainable resource use, thereby strengthening the policy basis for soil restoration, monitoring, and sustainable management under the Soil Strategy for 2030 and the SMRD.

2.2.5. The European Green Deal

The EU has committed to becoming the first climate-neutral continent by 2050, a political ambition articulated in the European Green Deal and legally anchored through the European Climate Law, which sets a binding target of climate neutrality by mid-century and at least a 55% net greenhouse gas (GHG) reduction by 2030 compared to 1990 levels.

Soil protection and restoration are embedded across some of the Green Deal's core strategies (see e.g. Montanarella and Panagos 2021b), notably the Biodiversity Strategy for 2030, the Farm to Fork Strategy (F2F), the Zero Pollution Action Plan (ZPAP), the Forests Strategy for 2030, and the European Climate Law (**Figure 2**). The Soil Strategy for 2030**,** the SMRD, and the Nature Restoration Regulation are embedded within and support the implementation of the BDS, strengthening its soil protection and restoration dimension.

Figure 2. The soil-related European Green Deal policies.



Source: JRC analysis.

2.2.5.1. Farm to Fork Strategy

The F2F Strategy seeks to transition toward sustainable food systems with reduced environmental footprint. Soil is recognized as the foundation of agricultural productivity, therefor its preservation is valorised as the Strategy's key objective (Montanarella and Panagos 2021b). F2F addresses key soil threats – erosion, organic matter decline, contamination, compaction, sealing, and biodiversity loss – while setting targets to reduce pesticide (by 50%) and fertilizer use (by 20%) by 2030, to restore polluted soils.

2.2.5.2. Zero Pollution Action Plan

The ZPAP extends soil governance into the pollution domain, aiming to improve soil quality by reducing nutrient losses and pesticide use, decrease ecosystem exposure to air pollution, and address soil contamination.

The Action Plan acknowledges that soil pollution poses significant risks to human health, soil quality, and the broader environment. It is also identified as a major driver of biodiversity loss and the decline of ecosystem services, including carbon sequestration. To address these challenges, the Plan introduces several soil-focused measures, notably the establishment of a framework for the regular assessment of soil contamination across the EU. Key components of this framework include the development of a priority watch list of soil pollutants and the provision of guidance for the safe, sustainable, and circular management of excavated soils. To monitor progress and evaluate emerging trends, the EC and the EEA will jointly publish a Zero Pollution Monitoring and Outlook Report every two years.

2.2.5.3. EU Forest Strategy for 2030

The EU Forest Strategy for 2030 is a sectoral instrument under the European Green Deal that sets the strategic guidance for sustainable forest management in the EU. It seeks to strengthen forest

carbon sinks, protect primary and old-growth forests, promote afforestation and reforestation, and enhance resilience to climate-related disturbances such as fires and droughts. Closely aligned with the BDS and climate legislation, the Strategy supports restoration efforts and reinforces the role of forests and forest soils as key carbon reservoirs within the EU's climate neutrality pathway.

2.2.5.4. European Climate Law

The Climate Law seeks to establish a climate-neutral and climate-resilient EU by 2050, highlighting the protection of carbon-rich soils – particularly wetlands and peatlands – and the mitigation of agricultural CO_2 emissions as key components of the transition.

The Fit for 55 Package aims to operationalise the binding climate target of GHG reduction by 2030. Introduced in 2021, it revises and strengthens key climate and energy legislation across sectors including energy, transport, buildings, industry, agriculture, and land use. A central component is the revised (2023) Land Use, Land Use Change and Forestry (LULUCF) Regulation which sets binding targets for net carbon removals[8] from land use and forestry, thereby reinforcing the role of forests and soils as natural carbon sinks (hence, operationalises the connection between F2F and the Fit for 55 Package). The revised LULUCF Regulation also acknowledges the potential of abandoned and degraded lands to enhance biomass production and contribute to carbon removals, thereby supporting the EU's climate neutrality objective.

2.2.5.5. Biodiversity Strategy for 2030

The Biodiversity Strategy for 2030 (BDS) aims to reverse ecosystem degradation and land impairment[9]. It establishes targets including protecting at least 30% of EU lands, restoring degraded ecosystems, expanding organic farming to 25% of cultivated land, reducing soil erosion, controlling urban sprawl, and advancing the identification and remediation of contaminated sites, the reintroduction of diverse landscape features, such as terraces and grass margins, into agricultural land.

Soil strategy for 2030

A central component of the BDS is the EU Soil Strategy for 2030, which establishes the objective of achieving healthy soils across the EU by 2050 and promotes greater societal engagement in soil protection. The Strategy provides a framework for sustainable soil management, the restoration of degraded soils, and enhanced soil monitoring, while combining voluntary and regulatory measures under the European Green Deal and respecting the subsidiarity principle and the competences of MS. Furthermore, it laid the foundation for the SMRD, which introduces a harmonised EU framework for soil monitoring and assessment and requires MS to monitor soil health, identify degraded soils, and take appropriate measures to improve their condition.

The EU Soil Strategy Actions Tracker tracks the progress of these concrete actions since the adoption of the EU Soil Strategy in 2021. The Tracker provides an overview on the status of the actions, information on the due date, recent updates, links to related EU policies, links to relevant

8 310 M t of CO2 equivalent by 2030.

9 The Strategy is grounded in the broader scientific evidence base on ecosystem degradation, including – inter alia – the 2018 'Land Degradation and Restoration Assessment' of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (https://ipbes.net/assessment-reports/ldr).

sources, and the main actors responsible for implementation. Currently, 67 out of 90 actions (74%) are marked as completed, 24 actions (21%) as in progress, and 4 actions (4%) as withdrawn (Broothaerts et al. 2025a)

Nature Restoration Regulation

The BDS is further operationalised through the Nature Restoration Regulation. The Regulation establishes legally binding targets to restore degraded ecosystems, including peatlands, wetlands, rivers, forests, grasslands, and marine areas. It requires restoration of at least 20% of EU land and sea areas by 2030, with full restoration of all ecosystems in need by 2050, prioritizing areas that maximize climate resilience, carbon sequestration, and disaster mitigation (e.g. floods, droughts, heat waves). The Regulation explicitly supports the increase of SOC stocks in farmlands[10] and the (re)conversion of arable land to carbon-rich ecosystems such as peatlands, directly addressing soil degradation while enhancing ecosystem services and farmland sustainability.

The overall Stock of Organic Carbon[11] and the specific Stock of Organic Carbon in Cropland Mineral Soils[12] serve as critical baseline indicators for assessing global climate mitigation, agricultural sustainability, and ecosystem resilience. Together, they quantify the amount of carbon stored within the earth's terrestrial sinks and track how human activities alter this vital pool.

Soil Monitoring and Resilience Directive

Although the SMRD is embedded within the BDS framework, it is discussed in a dedicated section (see section 2.2.6) due to its central importance for the future of soil monitoring and governance in the EU.

2.2.6. The Soil Monitoring and Resilience Directive

The Soil Monitoring and Resilience Directive (SMRD) is a key deliverable of the BDS. It constitutes a central legislative instrument with the overarching objective of achieving healthy soils across the EU by 2050, operationalised via the Soil Strategy for 2030. The SMRD establishes a harmonized definition of soil health – defining it as 'the physical, chemical and biological condition of soil that determines its capacity to function as a vital living system and to provide ecosystem services' (Article 3, Definition 5), a coherent EU-wide monitoring and assessment framework, and obligations for MS to identify, map, and remediate contaminated or degraded soils. It promotes sustainable soil management as a normative principle, including measures to limit soil sealing and land take, and adopts a territorial, bottom-up approach that relies on MS to contribute data and implement mitigation actions. By setting common standards for soil monitoring, reporting, and management, the SMRD provides the legal basis for coordinated restoration efforts, enforcement of remediation responsibilities, and the integration of soil health into EU environmental and land-use governance.

10 Article 11 of the Nature Restoration Regulation requires MS to implement measures aimed at achieving an increasing national trend in the stock of organic carbon in cropland mineral soils as one of the key indicators for the restoration of agricultural ecosystems (https://eur-lex.europa.eu/eli/C/2025/980/oj/eng).

11 Captures the entire terrestrial landscape, including forests, wetlands, peatlands, and grasslands. It reflects natural ecological equilibria, long-term geological stability, and broad biophysical climate zones.

12 Isolates highly managed ecosystems that are intensely vulnerable to human intervention. Unlike organic peatlands, mineral soils rely heavily on human management choices – such as tillage, cover cropping, and residue retention – to shift from net carbon sources into active carbon sinks.

The SMRD embodies a hybrid governance model that balances EU-wide harmonisation with the principle of subsidiarity. While common standards ensure comparability and policy coherence across MS, implementation remains nationally driven, allowing adaptation to diverse pedoclimatic conditions, land-use systems, and institutional capacities. This dual architecture addresses the historical fragmentation of soil protection across the EU and responds to longstanding calls for coordinated yet flexible soil governance (Panagos et al. 2025). By embedding soil health within a binding but territorially adaptable framework, the SMRD strengthens vertical policy integration between EU, national, and regional levels, reducing regulatory asymmetries and enhancing accountability in soil management.

A central innovation of the SMRD lies in the establishment of a harmonised soil monitoring architecture designed to support evidence-based policymaking and long-term trend assessment. The development of common indicators for SOC, erosion risk, contamination levels, soil structure, and soil biodiversity facilitates comparability across MS while enabling early warning mechanisms and adaptive management. As highlighted by Panagos et al. (2025), the integration of soil monitoring within broader EU environmental data infrastructures enhances transparency, reduces knowledge gaps, and supports the operationalisation of soil health targets under the BDS. By linking monitoring obligations with restoration and remediation requirements, the SMRD transforms soil data from merely descriptive inventories into actionable governance tools.

This institutional design reflects the transboundary character of soil degradation and its cascading effects on ecosystem services, as soil-related pressures frequently extend beyond national borders through sediment transport, nutrient leakage, and climate feedback mechanisms.

Beyond remediation, the SMRD signals a structural shift from reactive soil protection (Castelo-Grande et al. 2018) toward preventive and regenerative land stewardship. By promoting sustainable soil management, limiting soil sealing, and supporting restoration-oriented land-use practices, the Directive contributes to a broader transition toward climate-resilient and biodiversity-rich landscapes. Panagos et al. (2025) frame soil as strategic natural capital underpinning food security, climate mitigation, and ecosystem stability, thereby elevating soil health from a sectoral environmental concern to a foundational pillar of the European Green Deal transition. In this context, soils function as biophysical infrastructure supporting carbon sequestration, water regulation, nutrient cycling, and habitat provision, reinforcing their central role in achieving long-term environmental and societal resilience.

In connection with other instruments, the SMRD i) aligns with the CAP, which integrates measures to address soil degradation and promote sustainable farming practices, ii) complements the Water Framework Directive (Directive 2000/60/EC) by addressing soil-related pressures on water quality and hydrological systems, iii) reinforces the objectives of the BDS and the Nature Restoration Regulation, as healthy soils are essential for supporting diverse ecosystems and conserving biodiversity (Arias-Navarro et al. 2024), and iv) expects that Mission soil will provide new findings and scientific evidence for soil related indicators.

Besides, the scale[13] and economic framing[14] of soil degradation in the EU strengthens the rationale of the SMRD within the BDS 2030 strategy, reinforcing its strategic relevance within the EU sustainability transition (Panagos et al. 2025).

2.2.7. Carbon Removals and Carbon Farming Regulation

In 2024, the EU adopted Regulation 2024/3012 on a Union certification framework for permanent carbon removals, carbon farming and carbon storage in products, creating the first EU-wide voluntary system to certify climate-positive activities aimed at removing carbon from the atmosphere or reducing soil emissions. The Carbon Removals and Carbon Farming (CRCF) Regulation establishes harmonised quality criteria, monitoring, reporting and verification requirements, and independent third-party certification procedures to ensure the environmental integrity, transparency and comparability of removal and emission-reduction activities[15] across MS. Implementation of the CRCF Regulation is supported by accompanying secondary acts, including the Implementing Regulation (EU) 2025/2358, which lays down technical rules on certification schemes, certification bodies and audits, and by Delegated Acts adopted to define detailed certification methodologies for specific types of removal activities (e.g. permanent removals and carbon farming) as they become available in 2026 and beyond.

While carbon removals are not a standalone policy domain, they constitute a climate mitigation objective embedded within the Union's broader climate architecture, notably the European Climate Law and the revised LULUCF Regulation, which set binding targets for GHG reductions and land-based carbon sinks. Within this governance framework, carbon farming represents a policy instrument approach promoted by the EC to enhance carbon sequestration in agricultural soils and biomass through land management practices. Carbon sequestration is strategically embedded in the European Green Deal and the EU Soil Strategy for 2030 and operationalised under the CAP 2023–2027 via eco-schemes, agri-environment-climate measures, and national Strategic Plans. The CRCF Regulation thus provides the formal certification layer that connects soil carbon management and other removal activities with the EU's climate neutrality objectives, strengthening the integration of land-based mitigation into the Union's climate accounting and incentive structures.

2.2.8. The Digital Europe Programme

The Digital Europe Programme (DIGITAL) is a strategic EU funding instrument that entered into force in May 2021. With a budget of over €8.1 B under the 2021–2027 Multiannual Financial Framework, it supports capacity building in high-performance computing, artificial intelligence (AI), cybersecurity, advanced digital skills, and interoperable cloud and data infrastructures. Its aim is to accelerate the digital transformation of European society, economy, and public administrations, promoting the broad uptake of digital technologies to enhance competitiveness, resilience, and technological sovereignty. DIGITAL operates in synergy with other EU instruments such as Horizon Europe and the Connecting Europe Facility and supports European Digital Innovation Hubs to help

13 More than 60% of European soils are currently classified as unhealthy.

14 Even when applying cautious estimates, the overall annual economic burden of soil degradation across the EU is projected to range between approximately €80 and €140 B.

15 Permanent carbon removals, carbon storage in long-lasting products, carbon farming removals, and soil emission reductions (https://eur-lex.europa.eu/eli/reg/2024/3012/oj/eng).

Small and Medium-sized Enterprises and public actors integrate advanced digital solutions. These digital capabilities are crucial for evidence-based policymaking and data-driven governance across EU policy domains.

Digital capacities are central to implementing the SMRD and broader soil governance, enabling large-scale collection, integration, and analysis of environmental data. The SMRD establishes a digital soil health portal to centralize georeferenced information and ensure accessibility for policymakers, scientists, and the public, supporting harmonized monitoring and reporting across MS. DIGITAL-funded high-performance computing and AI tools improve the analysis of soil health indicators, forecast soil degradation risks (e.g. erosion, sealing), and model ecosystem services such as carbon sequestration and nutrient cycling. EU-wide digital systems – including satellite-based Copernicus services, soil observatories, integrated farm data platforms, and on-the-ground monitoring networks – facilitate cross-border interoperability and link SMRD objectives with climate targets under the European Green Deal, biodiversity commitments under the BDS, and agricultural policy under the CAP[16]. Mission Soil funded projects such as AI4SoilHealth and SoilWise, illustrate how AI-driven digital twins, open data Application Programming Interfaces, and rapid soil assessment tools can enhance soil data availability, stakeholder engagement, transparency, and sustainable land management practices, reinforcing the systemic integration of soil health into EU climate, biodiversity, and agricultural governance frameworks.

2.2.9. The Chemicals Strategy

The Chemicals Strategy is a cornerstone of the EU's environmental agenda aimed at achieving a toxic-free environment and strengthening chemical safety across the Union. Adopted in October 2020 as a key action under the European Green Deal's ZPAP, the strategy outlines objectives to better protect human health and the environment, and to drive innovation toward chemicals that are safe and sustainable by design throughout their life cycle.

The Strategy intersects closely with EU soil policy because chemical contamination is a major driver of soil degradation. Soil protection objectives are addressed through the EU Soil Strategy for 2030 and the SMRD, which aim to monitor soil pollution, establish inventories of contaminated sites, and support actions to reduce harmful residues such as PFAS[17] and pesticides. These initiatives contribute to the EU's broader zero-pollution ambition and are complemented by sectoral frameworks such as the CAP, R&I under Horizon Europe, and the Mission Soil (see section 2.2.12), which promote sustainable soil management and the reduction of harmful chemical inputs.

2.2.10. The Nitrates Strategy

The Nitrates Strategy is operationalised through the Nitrates Directive (91/676/EEC), a cornerstone of European water protection policy. The Directive is designed to reduce water pollution caused by nitrates from agricultural sources and promote sustainable nutrient use. It requires MS to monitor nitrate concentrations in surface and groundwater, identify polluted waters, and designate Nitrate Vulnerable Zones where specific action programmes must be implemented to limit nitrate leaching and runoff. These programmes include restrictions on fertiliser application, limits on nitrogen from

16 Particularly via eco-schemes, conditionality, and CAP performance monitoring.

17 Per- and polyfluoroalkyl substances.

manure, requirements for manure storage, and the promotion of practices such as crop rotations and cover crops (OECD 2017). MS must also establish voluntary codes of good agricultural practice outside Nitrate Vulnerable Zones and report every four years on water quality and the effectiveness of the measures.

The directive also intersects with soil governance, as nitrogen management at the soil–water interface directly affects soil health, agricultural sustainability, and ecosystem functioning (EEA 2024). Excessive nutrient inputs contribute to soil structure degradation, GHG emissions, and broader environmental pressures, linking the directive with the European Green Deal and its zero-pollution ambition, as well as targets to reduce nutrient losses under the F2F Strategy and the BDS. Within the CAP, eco-schemes and agri-environment-climate measures promote practices such as precision fertilisation, soil cover, and crop diversification that reduce nitrate losses while supporting soil protection. Integrated land–water governance[18] further reinforces sustainable nutrient management, and promotes solutions that improve soil structure, enhance water retention, and reduce runoff and erosion. R&I under Horizon Europe, including the Mission 'A Soil Deal for Europe', support the development of tools and practices for nutrient sustainable soil management, contributing to improved soil resilience and reduced nitrate pollution. The Nitrates Directive also supports the achievement of the SDGs by contributing to more sustainable food systems (SDG 2), promoting improved water quality and groundwater protection (SDG 6) and helping reduce nutrient pollution that harms freshwater and marine ecosystems (SDG 14 and SDG 15).

An important development linked to the ongoing evaluation of the Nitrates Directive concerns the recognition of REcovered Nitrogen from manURE (RENURE) fertilisers. The evaluation examines whether the existing regulatory framework sufficiently supports nutrient recycling and technological advances in manure processing while maintaining the Directive's primary objective of protecting water quality. Pending completion of the evaluation, Commission Directive (EU) 2026/288 (https://eur-lex.europa.eu/eli/dir/2026/288/oj/eng) introduced an interim framework allowing, under strict environmental safeguards, the use of certain RENURE fertilisers above the conventional 170 kg N ha^{-1} yr^{-1} manure application limit, thereby promoting circular nutrient management without compromising environmental protection.

2.2.11. The Sewage Sludge Directive

Adopted in 1986, the Sewage Sludge Directive (86/278/EEC) represents one of the earliest EU legal instruments addressing soil protection through the regulation of sludge use in agriculture. The directive aims to protect soils, vegetation, animals, and human health from the potential adverse effects of sewage sludge while encouraging its safe and beneficial reuse as a source of organic matter and nutrients. It establishes limit values for heavy metals in both sludge and soils, requires regular monitoring, and sets conditions for sludge treatment and application to agricultural land. Although primarily developed within the context of waste and wastewater management, the directive is directly linked to soil protection because it regulates the addition of organic residues to agricultural soils and seeks to prevent the accumulation of contaminants. A 2023 evaluation by the EC concluded that the directive has largely achieved its original objectives but is now considered outdated in light of emerging environmental challenges, including the presence of organic

18 Under the Water Framework Directive (Directive 2000/60/EC) and the European Water Resilience Strategy (https://commission.europa.eu/topics/environment/water-resilience-strategy_en).

pollutants, microplastics, and antimicrobial resistance in sludge. While no legislative revision has yet been adopted, the evaluation highlights the need to modernize the framework and better align it with current EU environmental and circular economy policies.

2.2.12. EU Research and Innovation Framework Programmes and HORIZON

Since the early 2000s, soil-related research within the EU has gradually transitioned from fragmented thematic projects in early Framework Programmes (FPs) to a structured, mission-oriented innovation framework aligned with strategic sustainability goals – illustrating the maturation of EU soil governance.

During the **Fifth and Sixth Framework Programmes** (FP5: 1998–2002; FP6: 2002–2006), soil research was embedded within broader environmental and agricultural priorities, addressing land degradation, erosion, soil fertility, and sustainable land management. Although no dedicated soil initiative existed, these programmes strengthened the scientific foundations for soil monitoring, modelling, and ecosystem assessment.

Under the **Seventh Framework Programme** (FP7: 2007–2013), research investment expanded significantly in areas linking soil carbon dynamics, ecosystem services, land-use change, and climate interactions. Improved datasets and modelling capacity – particularly through the Joint Research Centre (JRC) – enhanced Europe's ability to quantify soil erosion, SOC, and land degradation trends. This growing evidence-base reinforced the policy momentum generated by the 2006 STS and supported the integration of soil considerations into agricultural and environmental governance.

Horizon 2020 (2014–2020) marked a further shift toward systemic sustainability research. Soil health became increasingly connected to climate mitigation and adaptation (for example the European Joint Programme on agricultural soils – EJP SOIL), biodiversity conservation, circular bioeconomy strategies, and sustainable food systems. While soil remained embedded within broader clusters, the programme laid the conceptual groundwork for a more impact-oriented approach to R&I.

A structural transformation occurred with the launch of **Horizon Europe** (2021–2027), which introduced five EU Missions, i.e., 1) Adaptation to Climate Change, 2) Cancer, 3) Restore our Ocean and Waters, 4) Climate-Neutral and Smart Cities, and 5) A Soil Deal for Europe, designed to deliver measurable societal impact in support of the European Green Deal.

Reviewing four decades of EU-funded soil research, Arias-Navarro et al. (2023) found that European investments exceeding €5 billion have significantly advanced knowledge on soil processes, degradation, ecosystem services, and sustainable management. The analysis highlights a shift from sector-specific studies towards integrated soil health approaches that support climate action, biodiversity conservation, and food security. The authors emphasize that future research should focus on harmonised soil monitoring, improved soil data infrastructures, and the implementation of the EU Soil Strategy for 2030 and the SMRD, thereby supporting the goal of achieving healthy soils across Europe by 2050.

2.2.12.1.Mission Soil

The Horizon Europe Mission 'A Soil Deal for Europe' (Mission Soil) represents the first dedicated EU R&I framework explicitly centred on soil health. Mission Soil aims to establish 100 Living Labs[19] and Lighthouses[20] by 2030 to co-develop and test – from local to continental and eventually global scale – solutions for sustainable soil management, restoration of degraded lands, enhanced soil biodiversity, and improved soil monitoring systems. The Mission advocates a set of eight ambitious objectives (**Figure 3**), namely i) Reduce land degradation, ii) Conserve and increase SOC stocks, iii) No net soil sealing, iv) Reduce soil pollution and enhance soil restoration, v) Prevent erosion, vi) Improve soil structure, vii) Reduce the EU global footprint of soils, and viii) Increase soil literacy in society across MS. It directly supports the EU 'Soil Strategy for 2030' and advances targets related to Land Degradation Neutrality (LDN) (Orr et al. 2017; Feng et al. 2022) and climate resilience. In parallel, Mission Soil strengthens the societal engagement/citizen science soil health pillar by leveraging the CAP dissemination/ collaboration instruments such as the European Innovation Partnership for Agricultural Productivity and Sustainability (EIP-AGRI) and Agricultural Knowledge and Innovation Systems (AKIS). Between 2021-2022, projects funded under the Mission Soil were allocated more than €250 M, reflecting a substantial early investment phase (Arias-Navarro et al. 2023). Overall financial support is projected to approach €1 B by 2028, indicating a long-term commitment to scaling up R&I efforts on soil health (Panagos et al. 2024a).

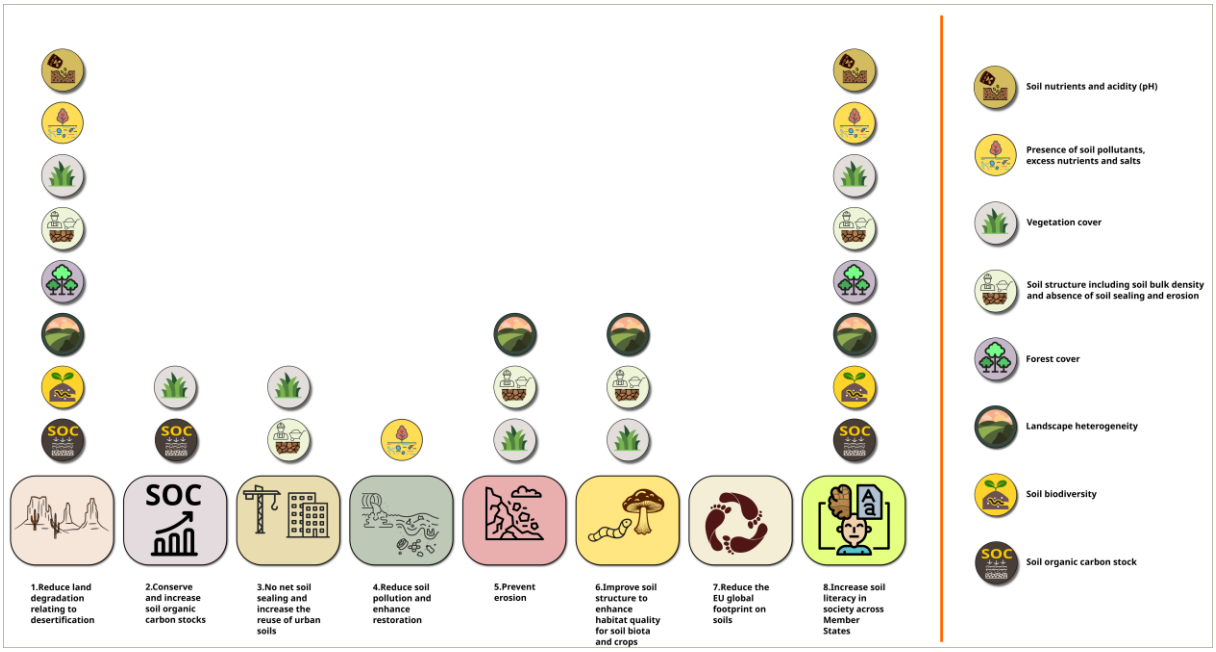
Moreover, the Mission Soil extends beyond the R&I dimension of Horizon Europe by being in close alignment with the CAP. Its objectives are reinforced through the CAP's conditionality system, particularly the GAEC standards, where GAEC 1–3 relate to objective 1, GAEC 4–7 to objective 2, and GAEC 8–9 to objective 3.

Mission Soil also supports the development of harmonised soil health indicators and monitoring frameworks, including tools such as the European Soil Observatory (EUSO) Soil Degradation Dashboard, which integrates multiple indicators of soil degradation at the European scale (Panagos et al. 2024a). These efforts combine top-down pan-European assessments with bottom-up experimentation in Living Labs, generating the scientific evidence and data needed to guide land management and support the implementation of the SMRD. In this way, Mission Soil acts as a bridge between research, policy, and practical land management, helping translate scientific knowledge into concrete actions to restore soil health across European landscapes.

19 Regional real-life experimental (eco)systems, that create knowledge on soil health restoration, by providing solutions through the engagement and communication of multiple partners across territories and sectors.

20 Entities in or outside the Living Labs' boundaries, that have produced outstanding achievements in improving soil health and related ecosystem services. They operate as training 'schools', disseminating the soil-friendly solutions adopted.

Figure 3. The objectives (bottom) and indicators (right) of the Mission Soil.



Source: Panagos et al. (2024c).

2.2.12.2.Beyond Mission Soil: Cross-Mission Synergies

Soil objectives under Horizon Europe extend beyond the Mission Soil itself. The Mission 'Adaptation to Climate Change' contributes indirectly to soil resilience by promoting nature-based solutions (NBS), flood prevention, drought mitigation, and land-use planning strategies that reduce soil erosion and degradation. The Mission 'Restore our Ocean and Waters' addresses nutrient runoff, sediment transport, and catchment-scale management, thereby influencing soil conservation practices in agricultural and peri-urban landscapes. The Mission 'Climate-Neutral and Smart Cities' also intersects with soil protection through urban greening, reduction of soil sealing, and restoration of urban soils as carbon sinks and biodiversity reservoirs. Moreover, reducing soil pollution and ensuring the safety of soils and food chains is recognised as a contributing factor to lowering environmental risk factors for cancer within the Mission 'Cancer', especially through joint research actions that investigate how carcinogenic substances in soil affect human health and cancer risks. Even the Biodiversity-related components embedded across missions reinforce soil ecosystem restoration, given the central role of soil biota in ecosystem functioning.

Table 2 illustrates the influence of Horizon Europe Missions on soil health, demonstrating that EU policy increasingly recognizes soil as a cross-cutting component of climate, water, biodiversity, and urban sustainability transitions.

Table 2. Horizon Europe Missions and soil health functions.

Horizon Europe Mission	Mechanism of Influence	Soil Functions Affected
A Soil Deal for Europe	Living Labs, harmonized indicators, restoration projects, sustainable land management	Carbon sequestration, nutrient cycling, soil biodiversity enhancement, erosion control, contamination remediation
Climate Change Adaptation	NBS, drought/ flood management, landscape planning	Water retention capacity, structural stability, erosion

Horizon Europe Mission	Mechanism of Influence	Soil Functions Affected
		resistance, desertification resilience
Restore our Ocean and Waters	Nutrient runoff reduction, sediment control, catchment-scale management	Nutrient retention, reduced soil loss, improved soil–water interactions
Climate-Neutral and Smart Cities	Urban greening, reduction of soil sealing, brownfield regeneration	Soil carbon storage, infiltration capacity, urban soil biodiversity
Cancer	Monitoring and mitigation of soil contaminants, safe food production, reduction of exposure to carcinogenic substances	Contaminant reduction, maintenance of soil chemical safety, healthy soil–food interactions, reduced bioaccumulation of toxicants

Source: JRC analysis.

The cross-cutting nature of soil health was further recognised through joint calls with other Horizon Europe Missions, reflecting the interconnectedness of soil health with climate change, biodiversity, water, and food system sustainability.

2.2.13. Global initiatives and their spillover effect on EU soil policy

Modern EU soil policy is also shaped by global frameworks such as the 2030 Agenda for Sustainable Development and its Sustainable Development Goals (SDGs) – particularly the Land Degradation Neutrality (LDN)[21] target. Introduced in 2015 by the UN, the SDGs represent an ambitious global programme aimed at advancing sustainable development, human well-being, and food security (Costanza et al. 2016). Soil health plays a central role in accomplishing this multifaceted objective (Keestra et al. 2016; Bouma et al. 2019). In brief, the achievement of SDG 2 (Zero Hunger), SDG 3 (Health), SDG 6 (Clean Water and Sanitization), SDG 12 (Sustainable Consumption and Production), SDG 13 (Climate Action) and SDG 15 (Life on Land) require the improvement of soil status For example, advances in SOC research contribute to several SDGs and underpin pathways toward climate neutrality by 2050 (Montanarella et al. 2016).

The Global Soil Partnership (GSP), established in 2012 under the auspices of the Food & Agriculture Organization (FAO), constitutes a voluntary global soil governance platform rather than a binding legal instrument. It operates as a multistakeholder coordination and knowledge mechanism that develops normative and technical guidance to promote sustainable soil management worldwide. Through instruments such as the Revised World Soil Charter (FAO 2015b), the Voluntary Guidelines for Sustainable Soil Management (FAO 2017), and global soil assessment and mapping initiatives, the GSP has played a significant soft-law role in shaping international soil discourse, influencing indicator development, and aligning soil governance with the SDGs. In governance terms, it occupies the global normative layer of soil policy architecture, informing the implementation of the UNCCD, which in turn frames regional strategies such as the EU Soil Strategy and mission-oriented instruments under Horizon Europe, thereby forming a multi-level governance continuum from voluntary global guidance to binding and operational policy mechanisms.

21 LDN – explicitly integrated into the 2030 Agenda as SDG 15, and more specifically Target 15.3 – is a policy objective aimed at safeguarding the capacity of land to sustain ecosystem services by counterbalancing degradation with actions that prevent, mitigate, and restore affected areas (UNCCD 2016).

2.2.14. Trade-offs and synergies in soil management within EU policy frameworks

Mitigation measures often generate synergies across ecosystem services, but may also involve trade-offs between environmental, economic and social objectives. For example, irrigation can combat soil degradation by enhancing land productivity, improving crop yields, and strengthening resilience to drought, but may be offset by groundwater overexploitation and contamination, increased soil erosion, waterlogging, and soil salinization. Moreover, maximizing crop yields, reducing GHG emissions, conserving biodiversity, maintaining SOC stocks, implementing drainage, and minimizing nutrient inputs are often conflicting objectives (Keesstra et al. 2018). These measures interact with several EU policy domains, including agriculture, climate, and water, highlighting the inter-connected and cross-sectoral nature of soil governance (Cowie et al. 2018). A list of trade-offs among soil-related management objectives within EU policy frameworks is presented in **Table 3**.

Table 3. Indicative examples of trade-offs among soil-related management objectives within EU policy frameworks.

EU Policy Instrument	Primary Objective	Competing Goal	Policy Domain	Soil-related Implication
CAP Greening (2014–20); CAP Strategic Plans (2023–27); BDS	Maximizing crop yields	Conserving biodiversity	Agriculture / Biodiversity	Allocating land to ecological focus areas or habitat restoration may reduce land available for intensive crop production
Nitrates Directive; F2F Strategy	Maintaining high agricultural productivity	Reducing nutrient inputs and water pollution	Agriculture / Water quality	Fertilizer restrictions reduce nitrate leaching and soil degradation but may limit yields if alternative fertility management is not adopted
Water Framework Directive; Water Resilience Strategy	Expanding irrigation to enhance drought resilience	Protecting water resources and soil quality	Water / Agriculture	Irrigation stabilizes yields but may lead to groundwater depletion, salinization, or waterlogging
LULUCF Regulation; Climate Law	Improving agricultural productivity through drainage	Preserving SOC and reducing GHG emissions	Agriculture / Climate	Drainage enables cultivation but accelerates SOC mineralization and increases CO_2 emissions in organic soils
Carbon Removals and Carbon Farming Regulation; LULUCF Regulation	Increasing soil carbon sequestration	Maintaining short-term agricultural productivity	Climate / Agriculture	Practices such as reduced tillage or rewetting peatlands enhance carbon storage but may constrain land-use options or reduce yields in the short term
Sewage Sludge Directive; Waste	Promoting waste recycling and circular economy	Safeguarding soil quality and minimizing contamination risks	Waste / Soil protection	Organic amendments improve soil fertility and organic matter but may introduce heavy metals or contaminants

EU Policy Instrument	Primary Objective	Competing Goal	Policy Domain	Soil-related Implication
Framework Directive				
European Green Deal; Fit for 55 Package	Expanding renewable energy infrastructure	Preserving soil functions and preventing land degradation	Climate / Land use	Infrastructure development may increase land take and soil sealing, affecting soil ecosystem services
Roadmap to a Resource-Efficient Europe; Nature Restoration Regulation	Urban development and infrastructure expansion	Limiting soil sealing and land take	Land use / Resource efficiency	Urbanization increases soil sealing and loss of fertile land, conflicting with soil conservation and restoration goals
Forest Strategy; LULUCF Regulation	Increasing forest carbon sinks	Maintaining agricultural land availability	Forestry / Agriculture	Afforestation enhances carbon storage and soil protection but may compete with agricultural land use
Soil Strategy for 2030; SMRD	Strengthening soil monitoring and environmental protection	Administrative burden and implementation costs	Governance / Policy implementation	Expanded monitoring improves soil governance but may increase reporting obligations and costs for MS and land managers

Source: JRC analysis.

2.3. Transformation in EU soil policy: from fragmentation to systemic governance

Soil policy at the EU level has undergone a profound transformation over the past decades, shifting from a fragmented landscape of sectoral provisions toward an increasingly integrated and dedicated governance framework. Having mapped the full range of EU soil-relevant policy instruments in Section 2.1 and positioned them within the broader chronological context of EU environmental governance in Section 2.2, this section traces the nature and dynamics of that transformation in greater depth. In line with the overarching objective of this chapter – to provide a comprehensive review of how EU soil policy has evolved – Section 2.3 examines three broad governance phases that characterise this trajectory: an early period of regulatory fragmentation prior to 2006, in which soil concerns were dispersed across uncoordinated sectoral frameworks; a transitional phase spanning 2006 to 2019, marked by the ambitious but ultimately unsuccessful proposal for a dedicated Soil Framework Directive and the institutional learning that followed its withdrawal; and a third phase of accelerated policy integration after 2019, in which the European Green Deal elevated soil health to a cross-cutting priority and culminated in the adoption of the SMRD. Across these phases, attention is given not only to what policies were adopted, but to the governance logic underpinning each period – including the shifting balance between voluntary measures and binding obligations, the growing role of monitoring and data in legitimising regulatory action, and the progressive alignment of soil governance with climate, biodiversity, and food system objectives.

Key milestones in EU soil-related policies are outlined in chronological order in **Table 4** and illustrated in **Figure 4**.

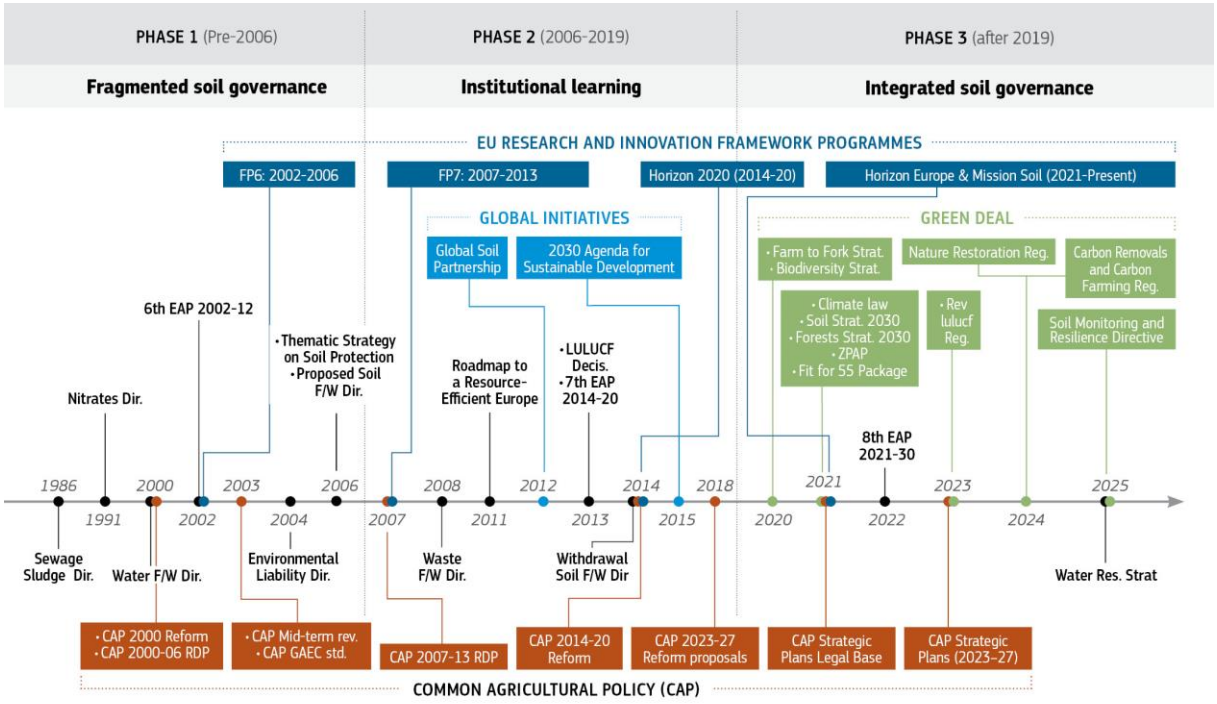
Table 4. Major milestones in EU soil governance and policy development (1986–2025).

Year	Instrument / Policy	Description / Soil Relevance
1986	Sewage Sludge Directive (86/278/EEC)	Regulates the safe use of treated sewage sludge in agriculture by setting limits for contaminants and monitoring requirements
1991	Nitrates Directive (91/676/EEC)	Establishes binding measures to reduce agricultural nitrate pollution, forming the foundation of EU soil–water nutrient governance
2000	Water Framework Directive (Directive 2000/60/EC)	Introduces integrated river basin management and 'good status' objectives, indirectly addressing soil–water interactions
	Agenda 2000 CAP Reform	Establishes the two-pillar CAP structure, linking agricultural support to rural development and environmental measures
	Rural Development Programme (2000–2006)	Introduces agri-environmental measures supporting soil conservation and sustainable land management
2002	6th Environmental Action Programme (2002–2012)	Defines soil degradation as an EU priority and mandates development of a thematic soil strategy
2003	CAP Mid-Term Review (Reg. 1782/2003)	Introduces cross-compliance and GAEC standards linking farm payments to environmental and soil protection requirements
2004	Environmental Liability Directive (2004/35/EC)	Establishes liability mechanisms for environmental damage, including soil contamination
2006	STS	Provides the first comprehensive EU policy framework addressing soil degradation threats
	Proposed Soil Framework Directive (COM 2006b)	Proposes legally binding soil protection measures, though ultimately not adopted (withdrawn in 2014)
2007-13	RDP (2007–2013)	Expands rural development funding for soil-protective and environmental land management practices
	FP7	Strengthens EU research on soil carbon, erosion processes, and land-use change dynamics
2008	Waste Framework Directive (2008/98/EC)	Regulates waste management and recovery, with implications for soil contamination and amendment use
2011	Roadmap to a Resource-Efficient Europe	Introduces the 'no net land take by 2050' objective, linking soil sealing to resource efficiency policy
2012	Global Soil Partnership	**Global governance context influencing EU soil strategy** – Establishes an international platform promoting sustainable soil management and global soil data harmonization
2013	7th Environmental Action Programme	Reinforces soil protection and land degradation objectives within the 2014–2020 EU environmental framework
	LULUCF Decision (529/2013/EU)	Introduces accounting rules for land-based carbon emissions and removals, integrating soils into EU climate policy
2014	Withdrawal of Soil Framework Directive	Removes the proposed EU soil directive following prolonged political deadlock in the Council
	CAP Reform 2014–2020 (Greening)	Introduces greening measures including Ecological Focus Areas and permanent grassland protection with soil co-benefits
	Horizon 2020 (2014–2020)	Integrates soil within climate, biodiversity, and ecosystem research funding priorities
2015	2030 Agenda for Sustainable Development	**Global governance context influencing EU soil policy** – Establishes Land Degradation Neutrality (SDG

Year	Instrument / Policy	Description / Soil Relevance
		15.3), embedding soil protection within global sustainability targets
2018	CAP Reform Proposals (2023–2027)	Introduces enhanced conditionality and performance-based delivery for soil-related agricultural measures
2019	European Green Deal	Establishes climate neutrality by 2050 as the overarching framework shaping soil-relevant EU policies
2020	Biodiversity Strategy for 2030	Embeds soil protection within ecosystem restoration and biodiversity enhancement objectives
	Farm to Fork Strategy	Sets reduction targets for pesticides and fertilizers, addressing key drivers of soil degradation
	Chemicals Strategy for Sustainability	Strengthens regulation of hazardous substances, addressing soil contamination risks
2021	Climate Law	Legally binds the EU climate neutrality target, reinforcing the role of land-based carbon sinks
	Soil Strategy for 2030	Establishes the objective of achieving healthy soils across the EU by 2050
	Zero Pollution Action Plan	Expands EU pollution control policy to include soil contamination prevention and remediation
	Forests Strategy for 2030	Promotes sustainable forest management to enhance soil carbon storage and ecosystem resilience
	Fit for 55 Package	Revises climate legislation including LULUCF targets affecting soil carbon accounting
	Digital Europe Programme	Supports digital infrastructure and tools for environmental and soil monitoring systems
	CAP Strategic Plans Legal Base (Reg. 2021/2115)	Establishes the legal framework for eco-schemes and enhances soil-related conditionality under the CAP
	Horizon Europe (2021–present)	Advances soil research through the Mission 'A Soil Deal for Europe' (a.k.a. Mission Soil) and integrated sustainability programmes
2022	8th Environmental Action Programme	Aligns EU environmental policy with Green Deal objectives for the 2021–2030 period
2023	Revised LULUCF Regulation (EU 2023/839)	Sets binding land-based carbon removal targets, strengthening soil carbon policy integration
	Proposal for a Soil Monitoring and Resilience Directive (SMRD)	Proposes a harmonized framework for soil health monitoring and sustainable management
	CAP Strategic Plans (2023–2027)	Implements eco-schemes and conditionality measures enhancing soil protection at MS level
2024	Nature Restoration Regulation (EU 2024/1991)	Establishes legally binding ecosystem restoration targets with direct soil recovery implications
	Carbon Removals and Carbon Farming Regulation (EU 2024/3012)	Creates an EU certification framework for carbon removals including soil carbon sequestration
2025	CRCF Implementing Regulation (EU 2025/2358)	Defines technical standards and verification rules for certified soil and land-based carbon removals
	Water Resilience Strategy	**Strategic initiative/communication** – Strengthens integrated water–soil management to enhance drought resilience and sustainable land use
	SMRD (EU 2025/2360) enters into force	The first EU-wide framework for soil health monitoring is established; MS are required to transpose its provisions into national law by 2028

Source: JRC analysis.

Figure 4. Timeline of major milestones in EU Soil Policy (1991–2025).



Source: JRC analysis.

2.3.1. Phase 1: Fragmented soil governance (pre-2006)

Prior to 2006, soil protection at EU level was characterized by regulatory fragmentation. At EU level soil remained the only major environmental medium without a dedicated legislative framework. Water (Water Framework Directive), air (Ambient Air Quality Directive) and waste (Waste Framework Directive) were all governed through binding horizontal directives. Soil-related provisions were instead dispersed across sectoral instruments, including the CAP (section 2.2.1), the Sewage Sludge Directive (section 2.2.11), the Nitrates Directive (section 2.2.10), the Environmental Action Programmes (section 2.2.4) and the Environmental Liability Directive, among others. No overarching soil-specific legal architecture existed. This structural gap meant that soil health was regulated only indirectly, relying largely on non-harmonized national standards that led to uneven protection.

This fragmented governance landscape ultimately provided the political and institutional context that motivated Thematic Strategy for Soil Protection and the proposal of the Soil Framework Directive in 2006 (section 2.2.2).

2.3.2. Phase 2: Failed legislative attempt and institutional learning (2006–2019)

In 2006 the EC adopted the Thematic Strategy for Soil Protection (section 2.2.2), including the proposal for the Soil Framework Directive with the objective of establishing an EU-wide legal framework for soil protection. However, it was never adopted and was formally withdrawn in 2014,

after nearly a decade of stalled negotiations, largely due to political resistance related to subsidiarity[22] concerns and national land-use sovereignty.

Following this withdrawal, soil protection continued through integration into existing sectoral policies rather than through a dedicated horizontal directive. This marked a transition from an attempted binding legislative framework toward incremental policy integration across agriculture, climate, biodiversity, and research instruments.

Until 2019, policy development remained relatively limited and fragmented, with soil primarily addressed through voluntary, sectoral, or incentive-based instruments including the CAP greening measures. While these initiatives contributed to improved management practices in certain contexts, they proved insufficient to halt cumulative degradation or ensure systematic restoration.

In this sense, the period following the withdrawal of the Soil Framework Directive can be understood less as a 'failure' than a transitional phase. Its abandonment did not halt the evolution of EU soil policy; rather, it initiated a phase of institutional learning and conceptual reframing that gradually laid the foundations for a more integrated and evidence-based approach to soil governance that began to emerge in the early 2020s (Phase 3). The objectives were also gradually integrated into multiple EU instruments (**Figure 1**).

During this period, policymakers increasingly recognized that soil policy could not succeed as an isolated environmental instrument. Effective governance required clearer definitions and measurable indicators of soil health, as well as greater political acceptance[23] among MS. At the same time a conceptual reframing occurred, evolving from a narrow focus on 'soil protection', associated primarily with damage mitigation, toward the broader concept of 'soil health', emphasizing the functional capacity of soils to deliver ecosystem services. This shift allowed soil to be integrated into cross-sectoral (cross-border) policy objectives, including climate mitigation through carbon sequestration, biodiversity conservation, and food security.

External frameworks further reinforced this transition. The adoption of the 2030 Agenda for Sustainable Development in 2015 and the introduction of the LDN target established an outcome-oriented logic. Although non-binding, SDG 15.3 provided an important international benchmark that framed soil degradation as a global sustainability challenge and strengthened the rationale for coordinated EU-level policy action.

2.3.3. Phase 3: Integrated soil governance under the European Green Deal (post-2019)

The launch of the European Green Deal in 2019 (see section 2.2.5) marked a turning point, triggering a rapid expansion of EU soil policy instruments. Soil transitioned from a peripheral environmental issue to a strategic natural capital underpinning climate, biodiversity, and pollution objectives. This accelerated development manifested in both regulatory innovation and cross-sectoral integration.

The EU Soil Strategy for 2030 played a central role in this transformation, reframing soil as a systemic resource, introducing soil health indicators and restoration objectives while linking soil

22 Decisions are made at the most immediate or local level possible, only shifting to higher levels if necessary.

23 Achievable by demonstrating solid socio-economic benefits.

management to broader goals such as climate neutrality and disaster risk reduction (see section 2.2.5.5). A key aspect of the EU Soil Strategy of 2030 is the SMRD (see section 2.2.6). The SMRD, entered into force in December 2025, establishes a harmonized definition of soil health, a coherent EU-wide monitoring and assessment framework, and obligations for MS to identify, map, and remediate contaminated or degraded soils. MS are required to establish and regularly update inventories of potentially contaminated and contaminated sites, with progress reported to the European Commission every five years.

At the same time, soil considerations were increasingly embedded within other policy initiatives, including the ZPAP and the EU Climate Adaptation Strategy, reinforcing their cross-policy relevance. This strategic shift was accompanied by the emergence of legally binding instruments. The Nature Restoration Law introduced ecosystem-scale restoration obligations across the EU, while the Soil Monitoring Law established EU-wide soil health criteria, harmonised monitoring requirements, and clearer MS accountability. Together, these developments reflect a transition toward outcome-oriented governance, in which soil policy relies increasingly on measurable targets, harmonised reporting, and accountability mechanisms aligned with SDG 15.3 and LDN principles. Within this framework, soil degradation is increasingly framed as a systemic sustainability risk linked to climate change, biodiversity loss, and food security.

By 2024, the policy context reflected in the latest 'State of Soils in Europe 2024' Report (Arias-Navarro et al. 2024) differed fundamentally from the 'States of Soils in Europe 2010' Report of Jones et al. (2012). Soil governance had evolved from documenting degradation to actively monitoring and restoring soil health, reflecting both the conceptual transition toward soil health and the regulatory maturation enabled by the European Green Deal. The contrast between the two assessments also reflects advances in scientific knowledge and monitoring capacity. At the same time, it highlights that patterns of soil degradation in Europe cannot be understood independently of the policy frameworks through which soils are managed, underscoring the importance of governance structures in shaping soil health outcomes**.**

In short, the post-2019 era reflects a causal chain: decades of fragmented governance and legislative gaps created awareness of systemic weaknesses, global frameworks provided normative and monitoring tools, and the European Green Deal provided the political and legal momentum to embed soil health as a strategic EU sustainability objective.

2.4. Outlook

The transition from fragmented soil protection to a robust legislative framework marks a critical milestone (see section 2.3), but it does not in itself guarantee improved soil health outcomes. Concerns persist regarding the effectiveness of European soil-related policies in mitigating current challenges (Glæsner et al. 2014) and addressing upcoming risks (Montanarella et al. 2016). Accordingly, the success of future soil governance in the EU will strongly depend on the implementation capacity of regulations, their adaptability to accelerated transformations – including the climate change, rapid digitalisation, fast-evolving financial regulation and market-based mechanisms, shifting food system, demographic change and land tenure reforms, and changing societal values – and their integration across interlinked policy domains (**Table 5**). The overarching goal of soil policy is to evolve into a dynamic, inclusive, and evidence-based system, in which legal instruments are continuously informed by monitoring data and socio-economic feedback and actively adjusted in response to emerging pressures.

Table 5. Emerging drivers of future soil governance.

Driver	**Governance role/ Effect**	**Policy instrument**	**Expected soil health outcome**
Climate change & desertification	Risk amplifier; demands adaptation and resilience planning	Climate adaptation strategies and soil resilience measures under the European Green Deal & the SMRD	Increased vulnerability to erosion, SOC loss, and climate related soil degradation, prioritization of prevention in high-risk regions
Digitalization & AI	Decision support; improves targeted governance	SMRD requiring harmonized monitoring frameworks; digital reporting systems	Early detection of degradation trends; more efficient restoration responses
Food system resilience & geopolitical pressures	Strategic reframing; links soil health to broader food system objectives	CAP reforms; environmental objectives integrated with soil protection goals; food security strategies, trade policy	Increased investment in long-term soil productivity and functional stability
Legal accountability & environmental rights	Strengthens enforceability and compliance; accountability of soil protection obligations	Environmental Liability Directive, constitutional/environmental rights, courts	Reduced tolerance of degradation; clearer responsibilities for prevention
Sustainable finance & market-based drivers	Economic incentive; complements regulation; creates incentives for soil-friendly practices	Taxonomy Regulation for sustainable activities – guidance for biodiversity and ecosystem services; conditional finance	Incentivizes soil-friendly practices, though equity effects vary; risk of uneven access and compliance
Nature restoration & biodiversity spillovers	Policy spillover; embeds soil health into ecosystem-based governance	Nature Restoration Regulation	Nature Restoration Regulation establishes binding ecological restoration targets with co-benefits for soil structure, biodiversity, and ecosystem service delivery
Scientific uncertainty, thresholds, irreversibility	Precautionary driver; promotes conservative, preventive regulation	Embedded in multiple EU environmental directives. E.g. Soil strategy for 2030 underlines the need for precaution/monitoring to prevent degradation	Safeguarding of high-quality soils; avoidance of irreversible loss
Demographic change & land tenure dynamics	Social constraint; affects long term stewardship	Rural development, land tenure reform, social policy incentives; CAP rural development supports sustainable soil management	Continuity of soil management and restoration uptake
Cultural values, public perception, political salience	Enhances legitimacy and compliance	Education, awareness campaigns, participatory governance. Soil Strategy for 2030 emphasizes awareness, knowledge, and stakeholder engagement	Behavioural change supporting sustainable soil use

Driver	Governance role/ Effect	Policy instrument	Expected soil health outcome
Cross-border & transboundary processes	Coordination driver; promotes coordination among MS beyond national boundaries, international agreements	Soil Strategy for 2030 & BDS promoting cooperation	Reduced off-site impacts and shared degradation pressures

Source: JRC analysis.

Climate change, desertification, and migration

The climate change is expected to amplify soil degradation, intensifying erosion (Cerda et al. 2000; Panagos et al. 2021), organic matter loss (Yigini and Panagos 2016), salinisation (Shokri et al. 2024), and desertification (Briassoulis 2005, 2010), particularly in Mediterranean Europe. Combined with socio-economic pressures, these processes can drive migration (Bendandi 2020), rural marginalisation, and reduced regional resilience. Future soil governance will therefore need to go beyond traditional environmental protection, integrating risk management and territorial cohesion by aligning soil policy with climate adaptation, disaster risk reduction, and regional development strategies – such as the RDPs. In this context, healthy soils can act as a stabilising factor, reducing vulnerability to climate extremes and supporting sustainable livelihoods, whereas failure to protect them may worsen climate-driven displacement and undermine long-term socio-economic stability.

Digitalisation, AI, and data-driven governance

Digitalisation and the increasing use of AI will reshape soil governance by influencing how policy decisions are informed, prioritised, and implemented. As soil-related data streams expand, governance frameworks may increasingly rely on algorithmic tools to assess risk, allocate resources, and monitor compliance. While this offers opportunities for earlier detection of soil degradation and more targeted interventions or funding – indicatively, soil indicators may inform automated compliance checks (e.g. conditionality, subsidies, restoration areas) – it also introduces challenges related to transparency, accountability, and explainability. If decision-support systems are not carefully governed, there is a risk that complex soil processes are oversimplified or that obscure algorithms replace expert judgment reinforcing existing biases. Future soil governance will therefore depend not only on technological capacity, but also on robust institutional safeguards ensuring that digital tools enhance rather than substitute informed policy decision-making.

Food system resilience and geopolitical pressures

The growing recognition of food system vulnerability has elevated soil health from an environmental concern to a strategic policy issue. Climate extremes, supply-chain disruptions, and geopolitical instability[24] have highlighted the dependence of food security on resilient soils capable

24 Food abundance in the EU greatly depends on Ukraine soils. Ukraine is one of the top food producers and exporters in the world. The country is characterized as the 'breadbasket of the world', given the rich grain production. Unfortunately, the warfare between Ukraine and Russia tends to jeopardize its leading role in the global food production chain, having to deal with the loss of the sovereignty of highly fertile agricultural lands, extensive soil contamination (heavy metals and toxic substances as 'byproducts' of bombing), and the significant decline in grain production. This conflict complicated food security issues, not only in this sensitive region of Europe, but also around the globe. Shortages in yield productivity and food inflation have set global food supplies at risk, especially the capacities of poor, food-importing countries (e.g. African nations), threating their most vulnerable social groups/populations with malnutrition.

of sustaining productivity under stress (Zoebisch and DePauw 2002; FAO/IFAD/UNICEF/WFP/WHO 2017; UNCCD 2022). In this context, soil governance may increasingly be framed as a matter of strategic autonomy and long-term resilience rather than environmental compliance alone. This reframing strengthens the political rationale for long-term investing in soil protection and restoration, as degraded soils undermine yield stability and adaptive capacity (e.g. to droughts, floods). As a result, future soil governance is likely to be more closely aligned with agricultural, trade, and security policies.

Legal developments and environmental rights

An emerging influence on soil governance is the growing recognition of environmental rights and legal accountability mechanisms, e.g. the 'Polluter Pays Principle'[25] – in line with the ZPAP. As environmental litigation increases and concepts such as inter-generational equity and the right to a healthy environment gain legal weight, public authorities may face stronger obligations to prevent soil degradation. Courts are likely to play a greater role in evaluating the adequacy of soil protection measures, shaping governance not only through legislation but also through legal precedent. While this 'juridification' trend may strengthen enforcement and clarify responsibilities, it also requires; depends on clear legal definitions of soil health and degradation.

Sustainable finance and market-based drivers

Soil governance is increasingly intersecting with financial regulation and market forces. Emerging drivers include the 'Environmental, Social, and Governance' criteria[26], the Green Taxonomy rules[27], and ecological; climate-risk disclosure obligations. As financial institutions incorporate environmental performance into investment decision-making, soil health may emerge as a factor influencing land valuation, access to credit (Nkonya et al. 2016a), access to technologies and equipment (Giger et al. 2015), and eligibility for public or private funding (GEF/UNCCD 2016). This creates a powerful indirect governance mechanism, incentivising soil-friendly practices and climate adaptation beyond traditional regulation. However, it also raises concerns about equity, as smaller landholders or marginal regions may face greater difficulty meeting emerging financial benchmarks (Napier 1999; Reardon et al. 2009). Without adequate socio-economic safeguards, soil policy risks reinforcing inequalities by placing disproportionate burdens on vulnerable regions or groups. Future frameworks will need to balance the efficiency gains of market-based drivers with safeguards that prevent the exclusion or penalisation of vulnerable actors, e.g. by incorporating support mechanisms

25 The Polluter Pays Principle in soil health requires those responsible for soil degradation to bear the costs of remediation and measures to prevent future damage, ensuring that environmental damage is factored into business decisions (cost internalization). It applies broadly to industrial pollution, hazardous waste, and increasingly to land-use practices that contribute to erosion.

26 A set of criteria for evaluating a company's broader impact beyond financial performance. Instead of just measuring profits through traditional financial analysis, Environmental, Social, and Governance criteria assess how a business manages environmental responsibility, social impact, and corporate governance (https://greenly.earth/en-gb/blog/company-guide/esg-criteria-what-you-need-to-know).

27 The EU Green Taxonomy is a classification system that defines which economic activities can be considered environmentally sustainable based on science-based criteria. It serves to guide investments, prevent greenwashing, and align financial flows with the EU's climate, biodiversity, and environmental objectives. It covers activities contributing to six environmental objectives: climate change mitigation, climate change adaptation, the transition to a circular economy, pollution prevention and control, sustainable use and protection of water and marine resources, and protection and restoration of biodiversity and ecosystems. (https://finance.ec.europa.eu/sustainable-finance/tools-and-standards/eu-taxonomy-sustainable-activities_en).

for restoration, incentives aligned with soil health objectives, and recognition of regional disparities in degradation risk and adaptive capacity.

Nature restoration and biodiversity spillovers

The expansion of nature restoration[28] and biodiversity policies represents a significant indirect driver of soil governance. Soils are fundamental to ecosystem recovery, carbon storage, and habitat quality, making them central components of restoration objectives. As restoration targets become legally binding, soil conditions may increasingly be regulated through biodiversity and ecosystem-based frameworks. While this creates opportunities for policy synergy, it also risks treating soil as a secondary substrate – a 'means' – rather than an explicit governance objective. Future soil policy will need to ensure that soil health is explicitly recognised within restoration agendas to avoid repeating earlier patterns of indirect and fragmented governance.

Scientific uncertainty, thresholds, and irreversibility

Advances in soil science increasingly highlight the existence of critical thresholds and long recovery times for key soil functions. This growing recognition of irreversibility introduces a new driver for preventive governance. Where degradation may lead to permanent loss of soil functions, policy frameworks may prioritise prevention over restoration and impose stricter protection for high-quality soils. Scientific uncertainty itself thus becomes a governance driver, encouraging risk-averse approaches and long-term planning. Future soil governance is likely to reflect this shift, embedding precaution as a central principle.

Demographic change and land tenure dynamics

Demographic trends and land tenure arrangements are powerful yet often overlooked drivers of soil governance outcomes. Rural depopulation in marginal areas[29], ageing farming populations, land abandonment[30], urbanization[31], consolidation[32], absentee ownership and insecure tenure (Sklenicka et al. 2015; FAO 2022) can all reduce incentives for long-term soil stewardship. Where land users do not expect to benefit from future soil improvements, compliance with soil protection measures may be weakened. Reduced labour availability limits the adoption (Stocking and Abel 1992) and maintenance of conservation practices[33] and diminishes community engagement in soil stewardship. Future governance frameworks may therefore need to account explicitly for tenure structures and demographic realities, to support sustained management rather than short-term exploitation.

Cultural values, public perception, political salience

Public awareness and cultural perceptions play a critical role in shaping the durability of soil governance frameworks. Historically, soil degradation has suffered from low visibility and limited political salience, contributing to weak regulatory ambition. However, the growing concern over food

28 The Nature Restoration Regulation is a key element of the BDS.

29 Driven by natural and socioeconomic conditions and exacerbated by the climate change (Rigaud et al. 2018; Bendandi 2020).

30 Almost 11% of EU croplands are in risk of abandonment by 2030 (Perpina-Castillo et al. 2018).

31 Drives soil sealing (Scalenghe and Marsan 2009; Pistocchi et al. 2015).

32 Paves the way for mechanization and more intensive farming practices (Wang et al. 2014).

33 E.g. abandoned or poorly maintained terraces accelerate soil loss (Tarolli et al. 2019).

quality, climate resilience (Cowie et al. 2018), and landscape degradation may increase societal demand for soil protection. As soil becomes more closely associated with human health (Brevik et al. 2017), cultural heritage (MEA 2005), and territorial identity (UNEP-WCMC and ICCA Consortium 2021), political support for robust soil governance may strengthen. Afterall, policies persist only if constituencies understand and support them. Future policy effectiveness will therefore depend not only on technical design, but also on the ability to communicate soil health as a shared societal value.

Cross-border and transboundary soil issues

Many soil degradation processes, such as wind erosion, dust transport (Guerzoni et al. 1997; Rodriguez et al. 2001), cross-border eutrophication and diffuse pollution (Novotny 1999; Silva et al. 2019), transcend administrative and national boundaries. As these transboundary impacts become more evident, soil governance may require stronger coordination across regions and countries. This is particularly relevant in desertification-prone areas and shared agro-environmental zones. Future soil policy may therefore evolve toward greater regional cooperation and alignment with international frameworks – such as the UNCCD's LDN target, reinforcing the need for harmonised approaches beyond individual MS.

2.5. Concluding remarks

The evolution of EU soil governance over the past decades reflects a profound transition from fragmented, largely sectoral interventions toward an increasingly integrated and systemic policy framework. What began as a predominantly diagnostic and threat-based approach to soil protection has gradually matured into a broader vision centred on soil health, resilience, and long-term stewardship. This transformation has been driven by the convergence of scientific evidence, mounting socioeconomic pressures, and the recognition that healthy soils are indispensable for achieving strategic objectives related to food security, climate neutrality, biodiversity conservation, and human well-being. Recent developments – including the EU Soil Strategy for 2030, the SMRD, and the integration of soil objectives across the CAP and the European Green Deal – signal a decisive move toward outcome-oriented governance based on harmonised targets, accountability, and restoration commitments. Yet, significant challenges remain, including uneven implementation capacities among MS, limited coordination across institutions and policy sectors, and the need to balance harmonisation with subsidiarity. The future of soil governance in Europe will depend on the ability to strengthen cross-sectoral policy coherence, mobilise adequate financial incentives, and embed soil stewardship more deeply into territorial planning and economic decision-making. Ultimately, effective soil governance must evolve beyond regulatory compliance toward a shared societal commitment to safeguarding soil as strategic natural capital.

3. Changes in data availability

3.1. Introduction

Soil data and data sharing are fundamental for understanding soil processes and functions, assessing soil degradation, and supporting evidence-based decision-making in land management and environmental policy. Over the past decades, the volume and diversity of soil-related data have increased substantially due to advances in soil surveys, monitoring networks, Earth Observation, digital technologies, increased funding, and analytical methods. However, the growing availability of soil data has not automatically translated into improved accessibility, interoperability, or usability. Significant challenges remain regarding data fragmentation, inconsistent standards, limited data sharing, and institutional barriers that constrain the effective use of soil information.

Against this background, the main objective of this chapter is to examine the transformation of soil data availability and data infrastructures in Europe over the past decades. Particular attention is given to the shift from fragmented and largely isolated datasets toward increasingly integrated, interoperable, and policy-oriented soil information systems. Understanding this transformation is essential because robust soil governance, effective monitoring, and evidence-based policymaking depend not only on the generation of data, but also on the ability to share, integrate, and reuse information across institutions, sectors, and scales.

This chapter directly supports the broader objectives of the report by analysing the evolution of the knowledge and evidence base underpinning European soil policy, monitoring, and management. While Chapter 2 examined the transformation of soil governance and policy frameworks, the present chapter focuses on the data infrastructures, information systems, and data-sharing mechanisms that enable those policies to be implemented, monitored, and evaluated.

The chapter is structured as follows. Section 3.2 examines the scientific, policy, and socio-economic value of soil data, and identifies the persistent barriers – technical, institutional, legal, and resource-related – that constrain data accessibility and sharing. It then traces the evolution of European soil information systems across three successive phases: from the legacy data era and early classification-based mapping, through the harmonization of infrastructures and the emergence of integrated information systems, to the current phase of operational soil health monitoring supported by Earth Observation, digital tools, and FAIR data practices. The section further reviews major European and global platforms that have shaped soil data generation, harmonization, and dissemination – including ESDAC, LUCAS, SoilGrids, and SoilWise – while introducing the growing role of Big Data approaches in soil science. Section 3.3 examines the technological and institutional drivers underpinning this transformation, including advances in Earth Observation, Digital Soil Mapping, proximal and remote sensing, cloud computing, and artificial intelligence, alongside the evolving policy frameworks that are reshaping soil data governance. Section 3.4 explores remaining challenges and future perspectives, focusing on data integration, interoperability, FAIR data ecosystems, and the development of next-generation soil monitoring and decision-support systems at European and global scales. The concluding remarks in Section 3.5 reflect on the overall trajectory of European soil data architecture and the conditions required for soil information to become a fully operational resource for evidence-based governance and adaptive soil stewardship.

3.2. Soil data, accessibility, and knowledge gaps

From a scientific perspective, soil data are essential for understanding complex soil processes and their interactions with broader environmental systems. They support the quantification of soil degradation processes such as erosion (Lal 2001), contamination (Panagos et al. 2013a), organic matter decline, salinization (Ferreira et al. 2022; Shokri et al. 2024), etc., while enabling advances in Digital Soil Mapping, modelling, trend analysis, and data-driven approaches (Minasny and McBratney 2016; Wadoux et al. 2020). Integrating soil data across temporal and spatial scales is critical for developing a holistic understanding of the drivers, impacts, and feedback of land degradation and restoration processes (Orr et al. 2017; Cowie et al. 2018).

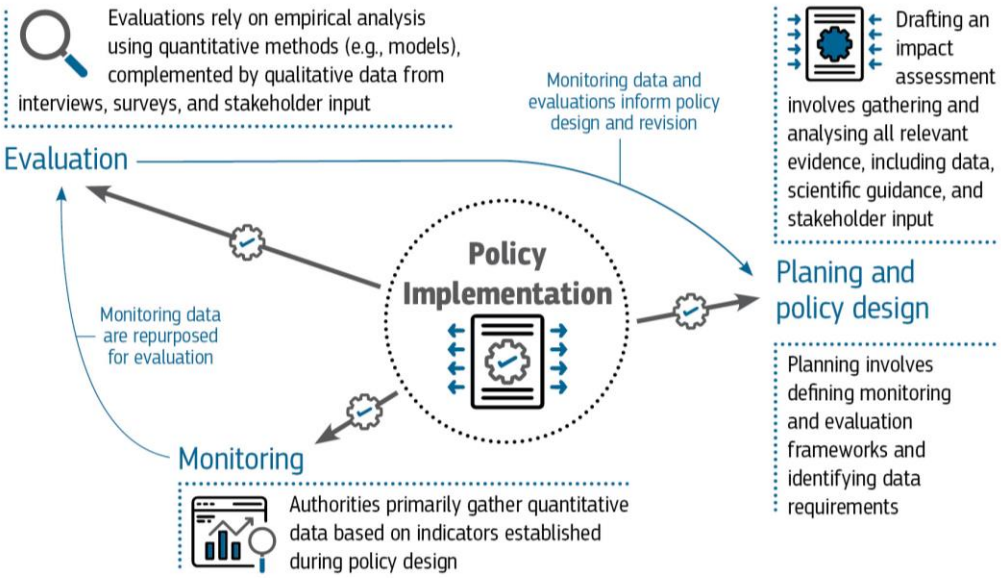
Beyond their scientific value, soil data are also a strategic resource for sustainable development and economic decision-making. In agriculture, they support precision farming (Wolfert et al. 2017), sustainable soil management, and productivity assessments (Kopittke et al. 2019). In the context of the climate change, they are essential for carbon sequestration estimates and adaptation strategies (de Rosa et al. 2023; Lugato et al. 2014). Soil information also underpins land-use planning, infrastructure development, and environmental risk assessments (Pistocchi et al. 2015). Increasingly, high-quality, interoperable soil data are becoming a valuable asset for the private sector, supporting sustainable investment, environmental risk management, supply chain transparency, regulatory compliance, and innovation, thereby enhancing the sustainable competitiveness of businesses and the bioeconomy (Panagos et al. 2025). Besides, soil degradation has direct socio-economic implications, affecting food security, migration, and economic stability (Bindraban et al. 2012; Nkonya et al. 2016b; Abu Hatab et al. 2019).

Policy and governance represent important domains of application, relying on soil data to support evidence-based[34] decision-making and to monitor progress toward environmental and sustainability targets. After all, better-informed soil policies enable more coordinated and efficient actions (Scholes et al. 2018). Indicators of soil health (Bonfante et al. 2020) and soil functions (Robinson et al. 2012) are used to assess progress from the field to international level – including frameworks such as the SDGs and LDN (UNCCD 2017; Keesstra et al. 2018). However, the development and application of such indicators require the availability of dependable, detailed, compatible soil records (Arias-Navarro et al. 2023).

Figure 5 illustrates how data underpin every stage of the policy cycle, from problem identification and policy formulation to implementation, monitoring, and evaluation. The figure highlights that evidence is not only required to diagnose environmental challenges and design appropriate interventions, but also to assess policy effectiveness and support adaptive management. Consequently, the quality, accessibility, and interoperability of soil data directly influence the ability of policymakers to develop and implement effective soil-related policies.

34 The EC's Better Regulation Guidelines (https://commission.europa.eu/system/files/2021-11/swd2021_305_en.pdf) defines evidence as 'data, information, and knowledge from multiple sources, including quantitative data such as statistics and measurements, qualitative data such as opinions, stakeholder input, conclusions of evaluations, as well as scientific and expert advice'.

Figure 5. Data use in a policy cycle. Each stage requires access to appropriate and reliable data, underscoring the leading role of evidence throughout the entire decision-making process.



Source: adapted from ECA (2022).

Despite the recognized importance of soil data across all these domains, a critical gap persists between data availability and data accessibility. Effective use remains constrained by diverse and interconnected barriers, spanning technical, institutional, socio-cultural, legal, and resources dimensions (**Figure 6**).

A central challenge lies in the fragmentation of soil information, which is distributed across multiple institutions, research projects, and countries[35], often with limited coordination and varying standards[36] (Morvan et al. 2008; Cornu et al. 2023). A substantial proportion of existing knowledge is also contained in legacy datasets derived from historical surveys and long-term experiments (FAO 2021). Differences among national soil information systems also hinder data exchange between MS and complicate the evaluation of European policies.

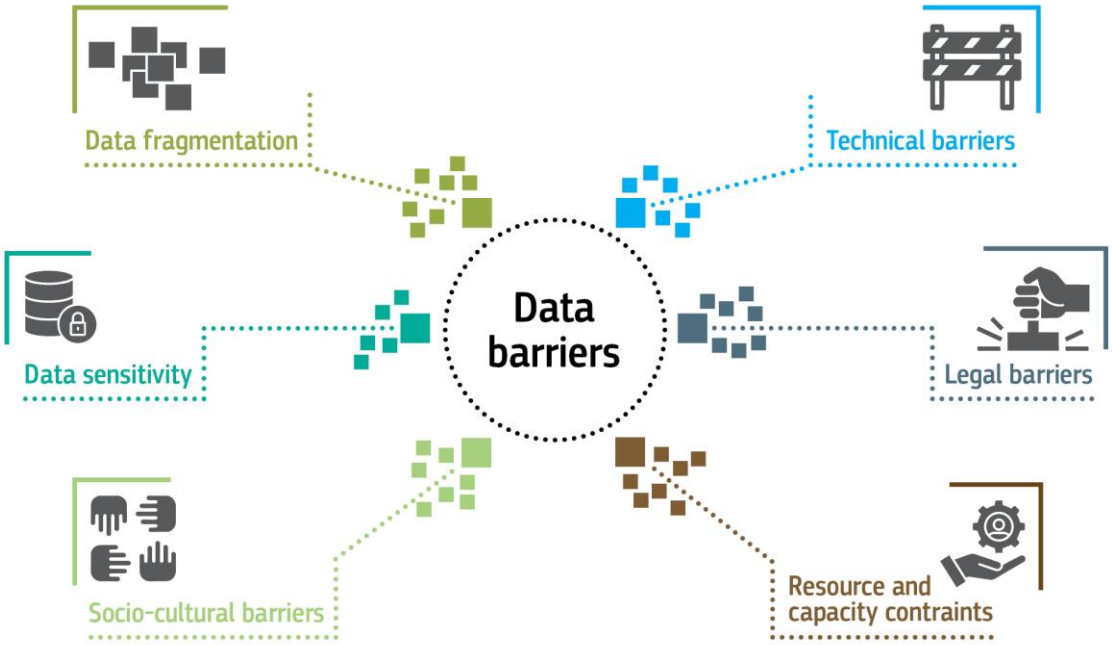
Technical barriers further exacerbate these limitations. While soil datasets are often rich in detail and temporal depth, they are frequently stored in incompatible systems and formats, insufficiently documented, lacking standardized machine-readable metadata, or only partially digitized (Arrouays et al. 2017). This heterogeneity constrains discoverability, reuse, and interoperability, ultimately limiting the integration of datasets across regions and scales, thereby reducing their usability for large-scale analyses and modelling. These challenges are further compounded by the intrinsic characteristics of many soil datasets, including their spatial sparsity and methodological heterogeneity. At the same time, the increasing volume and complexity of geospatial soil data

35 National soil databases and monitoring systems in the EU capture each MS's knowledge of local soils. Historical (legacy) archives from traditional sampling campaigns are often more representative than modern large-scale international databases – such as the LUCAS soil survey (Orgiazzi et al. 2018), SoilGrids (Hengl et al. 2017; Poggio et al. 2021), etc., providing higher detail and longer time series.

36 Sampling protocols, coverage, analytical methods, spatial resolution, and classification systems.

poses additional challenges for storage, processing, and analysis (Liakos and Panagos 2022). These issues reflect broader difficulties associated with the transition toward data-driven systems, and the management of large-scale datasets within the Big Data paradigm (Chen et al. 2014; Kumar et al. 2021).

Figure 6. Barriers in soil data use and sharing.



Source: JRC analysis.

Cornu et al. (2023) conducted two surveys among members of the European Joint Programme on agricultural soils (EJP SOIL) – titled '*Towards climate-smart sustainable management of agricultural soils*' – consortium (24 countries) to assess the status of national soil databases for agricultural soils across Europe. The analysis considered aspects such as data availability, database structure and content, temporal coverage (e.g. frequency of sampling campaigns), spatial coverage (e.g. number of sampling locations), and overall consistency, including data gaps. The findings revealed pronounced heterogeneity across countries, reflecting substantial differences in: i) the volume of available soil data, their historical development, and database organization, ii) sampling strategies and depths, iii) analytical methods used for soil parameter determination, iv) data-sharing policies, with access often constrained by national legal frameworks, and v) the type and completeness of information available, which vary according to policy requirements, geographic contexts[37], and the inclusion or omission of specific data categories[38] within national databases. Second-order insights (implications, structural issues, and emerging gaps) are presented in **Table 6**.

37 National and regional monitoring networks are more densely distributed in Northern and Eastern Europe compared to Southern European countries (Morvan et al. 2008).

38 E.g. SOC for climate change adaptation, trace elements to quantify soil pollution, soil texture and other inputs to model soil erosion, etc.

Table 6. Key systemic limitations affecting the integration of national soil databases in Europe.

Issue category	New (additional) insights	Policy relevance
Fragmentation of data systems	Coexistence of centralized national systems vs fragmented regional/local databases	Limits scalability and complicates EU-wide integration efforts
Inconsistent database purposes	Databases designed for mapping vs monitoring vs regulation differ in structure and variables	Affects suitability for longitudinal analysis and policy indicators
Temporal inconsistency	Data span from the 1920s to present, with irregular sampling intervals and gaps	Undermines trend analysis and baseline definition for SDGs / EU Soil Strategy
Legacy data incompatibility	Older datasets use outdated methods, classifications, and measurement protocols	Requires conversion functions or may be unusable without harmonization
Sampling design bias	Dominance of purposive sampling over statistically representative designs	Introduces bias and limits comparability across regions
Topsoil bias	Strong focus on topsoil, with limited subsoil data despite its importance for SOC and water storage	Leads to underestimation of carbon stocks and ecosystem functions
Incomplete parameter coverage	Systematic absence of key variables (e.g. biological indicators, hydraulic properties, organic pollutants)	Constrains development of comprehensive soil health indicators
Methodological non-equivalence	Some variables are not directly comparable (e.g. trace elements: total vs extractable fractions)	Prevents direct data integration even after harmonization
Metadata and documentation gaps	Missing information on sample pre-treatment and analytical procedures	Reduces reproducibility and data reusability (FAIR issues)
Legal and privacy constraints	Georeferenced soil data often restricted under GDPR-related interpretations	Major barrier to cross-border data sharing and EU observatories
Indicator development constraints	Lack of harmonized thresholds and reference values due to methodological diversity	Limits operationalisation of soil health policies
Ecosystem services gap	Existing databases are not designed to assess soil ecosystem services (e.g. water regulation, biodiversity)	Misalignment with modern policy frameworks (European Green Deal, SDGs)
Uneven geographic representation	Southern Europe is often under-sampled compared to smaller northern countries	Bias in continental-scale assessments
Cost and feasibility constraints	Biological and some physical indicators are expensive and methodologically sensitive	Explains their absence and limits future monitoring expansion
Need for hybrid solutions	Emerging approaches: pedo-transfer functions, scoring systems, federated learning	Indicates direction for future harmonization strategies

Source: Adapted and expanded from Cornu et al. (2023).

Beyond technical constraints, legal and socio-cultural barriers within the scientific and professional communities also play a decisive role in limiting data accessibility. Ownership, intellectual property rights, and institutional control can restrict data sharing, even when datasets are generated through publicly funded research. In parallel, a persistent reluctance among some researchers to share data – driven by concerns over misuse, lack of recognition, insufficient incentives, and potential loss of competitive advantage – continues to hinder the adoption of open data practices (Borgman 2011). This reluctance is reinforced by academic incentive systems, which primarily reward traditional

publication outputs – such as journal articles and citation metrics – over data sharing[39], thereby discouraging the dissemination of underlying datasets. As a result, many scientific publications are not accompanied by accessible data, limiting transparency and reproducibility in soil research (Gandrud 2015; Brunsdon and Comber 2021). Although the Findable, Accessible, Interoperable, and Reusable (FAIR) principles (Wilkinson et al. 2016) provide a widely accepted framework for improving data management and sharing, their implementation within soil science remains uneven. Within the European Union, the adoption of FAIR principles is further supported by legislative initiatives, notably the INSPIRE Directive, which establishes a common framework for the harmonisation and interoperability of spatial environmental data, and the Open Data Directive, which promotes the availability and reuse of public sector information. Together, these frameworks facilitate the integration, accessibility, and cross-border exchange of soil information, although significant challenges remain in achieving consistent implementation across MS and institutions. Finally, weak communication and coordination between data producers, data aggregators, and end-users often leads to inefficiencies, duplication of effort, and underutilization of existing information resources (see e.g. Shokri et al. 2025).

Another critical dimension concerns the sensitivity of soil data, which introduces additional constraints beyond technical and institutional barriers. Information on soil contamination – such as heavy metal concentrations (Ballabio et al. 2018, 2021, 2024; Silva et al. 2019) – or highly detailed georeferenced data linked to land ownership may raise environmental, economic, and privacy concerns. Such datasets are often subject to ethical considerations and regulatory frameworks, including those associated with the General Data Protection Regulation (GDPR), and their use or dissemination may require explicit consent from landowners. As a result, the sharing and reuse of sensitive soil information can be significantly constrained, particularly when potential risks for stakeholders are involved. These challenges highlight the need for carefully designed governance mechanisms that balance data openness with privacy protection, ethical responsibility, and risk management.

In addition to these structural and institutional challenges, resource and capacity constraints further contribute to persistent data gaps, particularly in regions with limited infrastructure for data collection, storage, and management. The lack of long-term investment in soil monitoring systems and data infrastructures exacerbates spatial inequalities in data availability, especially in areas most affected by land degradation (UNCCD 2022; Olsson et al. 2023).

Collectively, these limitations reveal a fundamental paradox: while the demand for high-quality soil data is rapidly increasing across scientific, environmental, and socio-economic domains, the systems required to ensure their availability, accessibility, and effective use remain fragmented and underdeveloped. Overcoming these barriers is essential not only for advancing soil science but also for enabling a holistic understanding of the drivers, impacts, and solutions of soil degradation, and for supporting sustainable land management in a rapidly changing world. Addressing these challenges requires a systemic approach that combines technological innovation, institutional coordination, and cultural change. Enhancing data standardization, promoting interoperability,

39 Career advancement, funding decisions, and institutional evaluations are still largely based on metrics such as publication counts, journal impact factors, and citation indices. In contrast, datasets, data curation efforts, and contributions to shared infrastructures are often undervalued or insufficiently recognized. While financial barriers – such as article processing charges associated with open access publishing – may further discourage openness in some cases, the primary constraint lies in the lack of formal incentives, recognition mechanisms, and standardized practices for data publication and reuse.

incentivizing data sharing, and strengthening collaboration across sectors are essential steps toward unlocking the full potential of soil data.

3.2.1. FAIR data principles

The FAIR data principles were formally introduced in 2016 through a landmark publication by Wilkinson et al. (2016), emerging from a 2014 workshop in Leiden, Netherlands, titled 'Jointly Designing a Data FAIRport.' This gathering brought together a diverse coalition of academics, industry representatives, funding agencies, and publishers united by a shared challenge: the existing digital ecosystem surrounding scholarly data publication was preventing researchers from extracting maximum benefit from their research investments (Wilkinson et al. 2016). The principles were subsequently refined by a dedicated working group established within the FORCE11 community – the Future of Research Communications and e-Scholarship – a body of scholars, librarians, archivists, and funders committed to improving knowledge creation and sharing. The result was a concise, domain-independent, and measurable framework intended to guide data producers and publishers worldwide (Banerjee 2025).

FAIR stands for Findable, Accessible, Interoperable, and Reusable (Wilkinson et al. 2016). Crucially, the principles apply not only to data in the conventional sense, but equally to the algorithms, tools, and workflows that lead to that data – all scholarly digital research objects benefit from their application (Wilkinson et al. 2016). A defining feature of the FAIR framework is its dual emphasis on both human and machine stakeholders. While humans can intuitively interpret contextual cues and semantic meaning, they cannot operate at the scope, scale, and speed demanded by contemporary data-intensive science (Wilkinson et al. 2016). Machines, acting as autonomous computational agents on our behalf, must therefore be capable of discovering, accessing, integrating, and acting upon data they have never encountered before. The FAIR principles provide what the authors describe as 'steps along a path' toward full machine-actionability, without mandating any specific technology, standard, or implementation solution.

Findability requires that data and metadata be easy to locate for both humans and machines. Concretely, this means assigning globally unique and persistent identifiers (such as DOIs) to all research objects, providing rich descriptive metadata, ensuring that metadata explicitly references the identifier of the data it describes, and registering datasets in searchable resources and indexes (Wilkinson et al. 2016).

Accessibility demands that once data is found, it can be retrieved using standardized, open, and freely implementable communications protocols – including appropriate authentication and authorization procedures where needed (Wilkinson et al. 2016). Importantly, even if data itself is restricted or removed, its metadata must remain accessible, preserving discoverability regardless of the data's availability (Wilkinson et al. 2016).

Interoperability addresses the ability of data and tools from non-cooperating resources to work together with minimal effort. This is achieved by using formal, broadly applicable languages for knowledge representation (such as RDF), applying vocabularies that themselves follow FAIR principles, and including qualified references to other datasets and metadata (Wilkinson et al. 2016). The challenge of interoperability is particularly acute in general-purpose repositories, where data types encountered by computational agents are inherently unpredictable (Banerjee 2025).

Reusability is ultimately the goal that the preceding principles enable (Wilkinson et al. 2016https://force11.org/info/the-fair-data-principles/). Data must be richly described with a plurality of accurate and relevant attributes, released with a clear and accessible data usage license,

accompanied by detailed provenance information, and aligned with domain-relevant community standards. Without unambiguous licensing and provenance, even well-described and accessible data may go unused due to legal uncertainty (Banerjee 2025).

Several repositories and platforms (e.g. Harvard Dataverse, FAIRDOM platform for Systems Biology, wwPDB structure archive, etc.) have pioneered FAIR implementation (Wilkinson et al. 2016). Practitioners implementing FAIR are advised to incorporate these considerations from the very beginning of a project, adopt domain-specific metadata standards, apply explicit usage licenses such as Creative Commons, and collaborate with data stewards who possess specialized knowledge in data governance and lifecycle management (Banerjee 2025).

The FAIR principles are explicitly technology-agnostic and modular, allowing their incremental adoption and enabling data providers to progressively improve the findability, accessibility, interoperability, and reusability of datasets (Wilkinson et al. 2016). They are equally applicable to sensitive or restricted datasets, as publishing rich metadata and clearly defined access conditions can achieve a high degree of FAIRness even when the underlying data cannot be openly shared (Wilkinson et al. 2016; Banerjee 2025). As research funders and publishers increasingly require robust data management and stewardship plans, the FAIR principles provide a practical and widely accepted framework for enhancing data quality, interoperability, reproducibility, and long-term reuse (Wilkinson et al. 2016; Banerjee 2025).

3.3. Transformation in soil data availability

Reliable and comparable soil data are fundamental for accurate soil health monitoring. However, inconsistencies in sampling strategies, laboratory methods, and data formats have historically limited the robustness of large-scale assessments and the calibration of predictive models. At the same time, legacy soil datasets and classification-based mapping approaches have produced fragmented and often difficult-to-integrate sources of soil information. In response to these challenges, international efforts since the early 2000s have increasingly focused on transforming disparate and largely descriptive datasets into harmonized, spatially explicit, and quantitative soil information systems. Central to this evolution has been soil data harmonization through standardized sampling protocols, analytical procedures, metadata standards, and quality assurance measures, enabling datasets collected across different regions and periods to be combined and compared more effectively. Together, these developments represent complementary components of the soil data value chain, spanning data collection, harmonization, analysis, dissemination, and reuse. They illustrate the broader evolution towards integrated, multi-source soil information systems capable of supporting modelling, long-term monitoring, and evidence-based policymaking across scales. This evolution has been characterized by a process of co-development, in which advances in data availability (further underpinned by the evolution of GIS technologies), analytical methods, and digital infrastructures have reinforced one another, enabling increasingly comprehensive and consistent representations of soil conditions and processes.

This section examines the evolution of soil information systems in Europe through three successive phases that reflect broader changes in scientific understanding, technological capabilities, and policy needs. The **first phase** was characterized by the development of soil classification systems, traditional soil surveys, and legacy datasets that established the foundations of soil knowledge but remained largely fragmented and descriptive. The **second phase** focused on harmonization and infrastructure building, driven by growing recognition of the need for interoperable datasets, standardized methodologies, and integrated information systems capable of supporting continental-scale assessments. The **third and current phase** is characterized by the emergence of operational

soil health governance, in which monitoring systems, Earth Observation, digital soil mapping, AI, and FAIR data infrastructures are increasingly integrated into policy implementation and decision-support processes. Together, these phases illustrate the progressive transformation of soil information from static inventories of soil characteristics towards dynamic, interconnected knowledge ecosystems that support evidence-based soil governance across multiple scales.

3.3.1. Phase 1: Foundations of soil Information systems and the legacy data era

Phase 1 describes the foundations of modern soil information systems and the characteristics of the pre-harmonization soil data landscape in Europe. It traces the evolution from early soil classification frameworks and expert-based mapping approaches to the development of national soil databases, monitoring programmes, and large-scale legacy datasets. While these efforts generated a substantial body of soil knowledge, they also produced a fragmented and heterogeneous information environment characterized by methodological inconsistencies, limited interoperability, and uneven data availability. Understanding these historical foundations is essential for explaining the subsequent shift towards harmonized monitoring frameworks, digital soil mapping, and integrated European soil information systems.

3.3.1.1. Early soil classification and classical mapping approaches

The need for systematic and coordinated soil classification led to the development of early classification systems, such as the United States Department of Agriculture (USDA) framework (Baldwin et al. 1938), followed by methodological refinements exemplified by the French Classification System (CPCS 1967). A turning point in soil classification was marked by the publication of the USDA '*Soil Classification – A Comprehensive System, 7th Approximation*' (Soil Survey Staff 1960), which introduced a more systematic, diagnostic, and hierarchical approach, and laid the foundation for the later '*Soil Taxonomy*' (Soil Survey Staff 1975), developed to support the interpretation and standardization of soil survey data.

These developments paved the way for internationally harmonized frameworks, most notably the FAO/UNESCO Soil Map of the World (FAO-UNESCO 1974), revised in 1988 to support global soil mapping efforts. This initiative was succeeded by the World Reference Base for Soil Resources (WRB), first released in 1998 and endorsed by the International Union of Soil Sciences. The WRB was designed as an international correlation and communication system, enabling the comparison and harmonization of different soil classification systems worldwide, while also providing a common framework later used in global soil mapping initiatives.

In parallel with the development of soil classification systems, soil information was traditionally collected through systematic field surveys and represented as polygon-based maps. These maps were delineated by soil experts based on field observations, aerial photography, and laboratory analyses, and were later digitized into Geographic Information Systems (GIS), typically as shapefiles. A prominent example is the European Soil Database, developed under the European Soil Bureau (Montanarella and Jones 1999), which provides harmonized soil information across Europe based on national soil surveys and expert-driven generalization. While these datasets constitute a cornerstone of continental-scale soil information, they are inherently based on discrete mapping units that assume homogeneity within polygons, often masking significant within-unit variability (Miller and Schaetzl 2016). These classification and mapping frameworks subsequently provided the basis upon which many national and international soil datasets were developed.

3.3.1.2. Legacy soil datasets: sources, uses, and limitations

Building upon the classification and mapping frameworks described above, soil information used in both legacy datasets and contemporary soil information systems originates from a wide range of sources, including national soil surveys, research projects, long-term field experiments, and soil monitoring programmes (ECA 2018). These datasets typically provide detailed point-based information on soil physical, chemical, and biological properties, often collected using standardized laboratory and field methods (Arrouays et al. 2017; Batjes et al. 2017).

However, despite their high analytical quality, such datasets are often spatially sparse and unevenly distributed, requiring interpolation and modelling to generate continuous aerial information (Hengl et al. 2017; Poggio et al. 2021). This limitation, combined with inconsistencies in data formats, sampling designs, and measurement protocols – particularly in older datasets – has posed significant challenges for data harmonization and integration across scales (Kumar et al. 2021; Cornu et al. 2023).

Over time, these diverse data sources have supported the development of numerous national, regional, and global soil databases maintained by organizations such as FAO, UNEP, the JRC, the International Institute for Applied Systems Analysis. Together, these databases have become essential resources for environmental assessment, land management, and policy support.

A substantial body of historical soil knowledge is also preserved in analogue soil maps. To prevent the loss of these valuable resources, major international initiatives have focused on their digitization and long-term preservation. One prominent example is the European Digital Archive of Soil Maps (EUDASM) established to safeguard historical soil maps that are vulnerable to physical deterioration and institutional loss. The archive provides open access to more than 6,000 high-resolution scanned soil and land resource maps from 135 countries, many of which constitute the only available soil information for specific regions. These maps remain an important source of legacy knowledge and continue to support soil mapping, land evaluation, and historical change analyses. At the global level, the Food and Agriculture Organization (FAO) has undertaken a similar effort through its Soil and Land Legacy Maps initiative. FAO has catalogued approximately 5,000 historical soil and land resource maps produced over the past century in collaboration with national authorities. In addition, around 1,200 maps have been scanned and made available in digital form to preserve the original information and associated metadata. Although many of these maps are not georeferenced and require further processing before integration into modern GIS environments, they represent an irreplaceable record of historical soil conditions and survey activities worldwide. ISRIC also hosts the World Soil Library of Maps and Reports (https://isric.org/focus-areas/soil-collections-and-education/), which preserves around 10,000 digitised legacy soil maps together with more than 17,000 reports and books, providing an invaluable archive for historical soil research and the digitisation of legacy soil information.

In addition to legacy surveys and long-term monitoring, large-scale R&I projects constitute a valuable, yet often underutilized[40], source of soil data. Over the past decades, EU-funded programmes (Arias-Navarro et al. 2023) and other international initiatives have produced extensive datasets on soil properties, processes, and ecosystem functions, covering aspects such as OC, erosion, contamination, and climate-soil interactions. These projects typically combine field

40 By not being shared; made public in a systematic way.

measurements, laboratory analyses, and modelling approaches, while also fostering methodological innovation and the development of new indicators. Despite their scientific potential, the outputs of these projects are frequently heterogeneous, fragmented across institutions, and not fully integrated into existing soil information systems. Repositories such as CORDIS and the European Soil Data Centre (ESDAC) (Panagos et al 2022b) are increasingly making these datasets accessible, offering opportunities for harmonization and reuse. Recognizing research project datasets as a complementary data source helps bridge the gap between historical legacy information and modern, integrated soil monitoring frameworks, supporting both continental-scale assessments and policy-driven applications.

These products constitute the primary historical sources of harmonized soil information and have been extensively used in environmental modelling, land management, and policy support. However, the aggregation and generalization inherent in large-scale harmonized products often result in simplified representations of soil diversity and spatial variability – particularly in Europe – due to their reliance on generalized assumptions regarding soil properties and the need for spatial extrapolation in data-limited contexts. Moreover, the predominantly polygon-based structure and relatively coarse spatial resolution of these products limit their ability to capture fine-scale heterogeneity (Kristensen et al. 2019).

These limitations have, in turn, driven the transition from traditional classification-based mapping towards more data-driven approaches, such as Digital Soil Mapping (see § 3.3.2.3), which leverage advances in Earth observation, proximal sensing, and computational methods to better represent the continuous and dynamic nature of soil variability.

3.3.1.3. Fragmented data under weak governance

Although substantial amounts of soil information had been collected across Europe by the beginning of the 21st century, the absence of a coherent European soil policy framework limited the integration and coordinated use of these resources. Soil information remained largely organized within national or regional systems developed for specific agricultural, forestry, environmental, or land-use planning purposes.

Efforts such as the establishment of the European Soil Bureau in 1985, which later evolved into the European Soil Bureau Network, marked important steps toward harmonisation. However, these initiatives initially focused on compiling existing national data rather than generating new, standardised observations – they contributed to data sharing but did not fully resolve the harmonization gap. As a result, European-scale soil assessments conducted in the 1980s, 1990s, and early 2000s relied extensively on expert judgement, literature synthesis, and model-based extrapolation.

This limitation is clearly reflected in the 'State of Soils in Europe 2010' Report, which emphasised that the knowledge base for many soil functions remained poorly developed and constrained by data scarcity and inconsistency (Jones et al. 2012). The lack of harmonised monitoring systems meant that: i) soil erosion estimates were largely model-based with limited validation, ii) SOC was represented through static inventories rather than measured trends, iii) salinisation and compaction were poorly quantified, often inferred from indirect indicators, iv) biodiversity was largely a data gap, with almost no operational indicators at European scale, v) soil sealing relied on coarse land cover datasets (e.g. CORINE), with limited spatial resolution, and vi) other physical (e.g. texture) and chemical properties (NPK, pH, etc.) were lacking.

Soil data during this period were therefore largely **static**, **fragmented**, and **descriptive**, reflecting a governance context in which soil protection remained weakly coordinated at the European level, and only indirectly through sectoral policies (see § 2.3; Phase 1). Although important efforts had been made to compile and share existing information, significant barriers to harmonization, interoperability, and long-term monitoring persisted. These limitations would become a major driver for the subsequent development of coordinated monitoring initiatives, shared data infrastructures, and digital approaches to soil information management.

3.3.2. Phase 2: Harmonization and the emergence of integrated soil information systems (2006–2019)

Phase 2 marks the transition from fragmented and largely descriptive soil information towards harmonized, interoperable, and increasingly quantitative soil data systems. Triggered by growing recognition of the limitations of existing datasets and monitoring frameworks, this period was characterized by major investments in data infrastructures, harmonization initiatives, and digital soil mapping approaches. At both European and global scales, new platforms, databases, and standards were developed to improve data accessibility, comparability, and spatial coverage. Together, these developments laid the foundations for modern soil monitoring systems and strengthened the evidence base required for environmental assessment, modelling, and policy implementation.

3.3.2.1. Characteristics of the transition period (2006–2019)

The introduction of the Thematic Strategy for Soil Protection (section 2.2.2) and the proposed Soil Framework Directive in 2006 marked a turning point in the evolution of soil information systems in Europe. Although the Directive was ultimately not adopted, the process revealed a fundamental challenge: the lack of harmonized, comparable, and measurable soil data capable of supporting effective policy implementation and evaluation. The launch of the ESDAC in the same year represented one of the first major institutional responses to this challenge, providing a platform for data harmonization, integration, and dissemination (Panagos et al. 2022a).

The limitations of the existing soil knowledge base were further highlighted in the 'State of Soils in Europe 2010' Report (Jones et al. 2012), which identified significant gaps in data availability, harmonization, and monitoring capacity. Many soil functions and threats could not be assessed consistently across MS due to methodological differences, uneven monitoring efforts, and limited spatial coverage.

During this period, soil policy continued to rely largely on sectoral and non-binding instruments, particularly through environmental conditionality under the Common Agricultural Policy. However, these instruments introduced reporting requirements, gradually increasing the demand for measurable soil indicators and standardized reporting systems. Global frameworks such as the 2030 Agenda for Sustainable Development adopted in 2015 and the LDN concept (SDG 15.3) reinforced the need for quantifiable, comparable, and repeatable metrics.

Overall, this period represents a transition in soil data systems in Europe. The key shift was from passive data compilation to active data generation and integration. The initiatives described below collectively laid the scientific, technical, and institutional foundations for the more sophisticated monitoring and governance systems that emerged during the subsequent Phase 3.

3.3.2.2. European data infrastructure: the European Soil Data Centre (ESDAC)

The ESDAC, launched in 2006, serves as the central repository and reference platform for soil-related data and information within the EU. Hosted by the EC's JRC, plays a key role in the collection, standardization, storage, and dissemination of soil datasets derived from European and national sources, supporting both scientific research and policy development (**Figure 7**). ESDAC integrates a wide range of data types, including soil properties, land use, topography, and climate-related variables, structured within a harmonized geospatial framework that ensures interoperability and accessibility across different user communities (Panagos et al. 2022b).

Figure 7. European Soil Data Centre (ESDAC) 2.0 and EU Soil Observatory.



Source: Panagos et al. (2022b).

Beyond its function as a data repository, ESDAC provides a comprehensive suite of derived products, including high-resolution maps, modelling outputs, and thematic datasets addressing major soil threats across Europe. These include datasets on soil erosion by water (e.g. RUSLE-based assessments), wind erosion susceptibility, SOC stocks, soil sealing, contamination, compaction, landslide susceptibility, biodiversity, nutrients, other physical and chemical properties. Many of these products are generated through the integration of in-situ measurements (e.g. the Land Use-Land Cover Area-Frame Survey; LUCAS), Earth Observation data, and modelling approaches, offering spatially explicit and policy-relevant information. ESDAC also supports the development of indicators used in EU environmental reporting frameworks, including those linked to the European Green Deal, the EU Soil Strategy for 2030, and LDN targets. Through its open-access policy and continuous updates, ESDAC enhances transparency, reproducibility, and the reuse of soil data, positioning itself as a cornerstone of the European soil knowledge infrastructure (Panagos et al. 2022b).

While ESDAC primarily functions as a data infrastructure and knowledge hub, it also forms a foundational component of the broader European soil monitoring architecture. Specifically, it underpins the activities of the EUSO, which builds upon ESDAC's data resources to support integrated soil monitoring, indicator development, and policy implementation at the EU level (Maréchal et al. 2022; Broothaerts et al. 2025b). The role of EUSO in advancing soil monitoring systems, linking data to policy frameworks, and advancing the soil health agenda is examined in detail in Chapter 4.

3.3.2.3. Digital Soil Mapping initiatives

Methodological evolution

A pivotal conceptual breakthrough underpinning all subsequent digital soil information systems was the formalization of the Digital Soil Mapping framework by McBratney et al (2003), and its critical retrospective appraisal (Minasny and McBratney 2016). Digital Soil Mapping is defined as the creation of spatial soil information systems through the use of field and laboratory observations, environmental covariates, and quantitative relationships derived from statistical and machine-learning models. Its theoretical backbone rests on Jenny's (1941) CLORPT model of soil formation – in which soil properties are expressed as a function of climate, organisms, relief, parent material, and time – which McBratney et al. (2003) extended by adding spatial position to yield the SCORPAN[41] framework. This reformulation transformed soil formation theory into a pragmatic, spatially explicit prediction model, enabling the quantitative mapping of soil properties and classes from environmental covariates at any scale (Wadoux et al. 2020).

Reflecting on a decade of practice, Minasny and McBratney (2016) attributed the rapid ascent of Digital Soil Mapping to a confluence of enabling factors emerging around the year 2000: the growing availability of digital elevation models and satellite imagery, increases in computational power, the maturation of data-mining tools and GIS environments, and a renewed institutional demand for spatially explicit, uncertainty-aware soil information. They noted that the number of pixels in published digital soil maps had grown exponentially since the early 2000s – a trajectory that has continued with the advent of cloud computing and global platforms. Critically, the authors observed that Digital Soil Mapping had by then moved decisively from a research curiosity into operational use, with applications spanning carbon accounting, land degradation assessment, precision agriculture, and global environmental modelling. They further identified the ambition of achieving global soil property coverage at 30 m resolution by 2030 as the next frontier – a goal now being actively pursued through initiatives such as GlobalSoilMap, SoilGrids, and national Digital Soil Mapping programmes. In this sense, the Minasny and McBratney (2016) paper serves not merely as a history of a subdiscipline but as a benchmark marking the transition from Phase 2 harmonization efforts to the integrated, data-driven monitoring ecosystems of Phase 3.

GlobalSoilMap

A major milestone in the transition from conventional to Digital Soil Mapping is the GlobalSoilMap initiative, launched in 2006 within the framework of the International Union of Soil Sciences Working Group on Digital Soil Mapping. The GlobalSoilMap aims to deliver globally consistent high-resolution soil data to support environmental modelling, land management, and policy development (Arrouays et al. 2017).

A central component is the systematic rescue, coordination[42], and integration of legacy soil data. These data are used to produce continuous gridded maps of key soil properties (e.g. texture, SOC,

41 SCORPAN represents the seven environmental predictors used in digital soil mapping, where S stands for existing soil properties, C represents climate factors like temperature, and O denotes organisms such as vegetation cover. R signifies relief or topography, P stands for the underlying parent material or geology, A represents the age or time factor of the landscape, and N denotes the spatial position or geographic coordinates.

42 Common framework on how soil data should be structured and produced; The SoilGrids subchapter (in 'Open-access platforms and digital soil mapping products') describes the real-world implementation/product.

pH, bulk density) across six standard depth intervals at approximately 90 m resolution, including uncertainty estimates (Arrouays et al. 2017).

By combining bottom-up approaches (based on national datasets; locally relevant) with top-down modelling strategies (ensuring spatial completeness and cross-border consistency), and leveraging advances in data availability, Earth Observation technologies, and Machine Learning methods, GlobalSoilMap provides a compatible yet spatially detailed representation of soil variability. It thus acts as a bridge between traditional soil surveys and modern, data-driven soil information systems (Arrouays et al. 2017, 2020).

SoilGrids

Building on the principles and specifications ıintroduced by GlobalSoilMap, SoilGrids (Hengl et al. 2017; Poggio et al. 2021) represents one of the most widely used operational implementations of digital soil mapping. Developed by ISRIC – World Soil Information and launched in 2013, SoilGrids employs machine-learning algorithms trained on hundreds of thousands of soil observations[43] and a large suite of environmental covariates (selected from an extensive pool of more than 400 layers), including climate, terrain, land cover, and Earth Observation data.

The platform produces high-resolution soil property maps (up to 250 m) for key variables such as soil texture, SOC, pH, coarse fragment content, and bulk density, across six standardized depth intervals. All outputs are harmonized according to international standards, ensuring interoperability with other soil monitoring frameworks and modelling approaches. Through its open-access architecture and continuous updates, SoilGrids has become a key resource for environmental modelling, ecosystem assessments, climate studies, and global soil monitoring efforts.

3.3.2.4. Global harmonization platforms

The Harmonized World Soil Database

The Harmonized World Soil Database, first released in 2008, is a global soil information system developed by the FAO and the International Institute for Applied Systems Analysis, providing harmonized data on soil physical, chemical, and morphological properties at approximately 1 km resolution[44]. It integrates numerous national and regional datasets into a unified GIS-based framework.

The updated version (v2.0) expands spatial coverage, increases the number of soil profiles, and improves vertical representation across seven standardized depth layers. It applies consistent classification aligned with FAO and WRB systems and includes a wide range of soil attributes linked to approximately 30,000 mapping units. Designed for global applications, the Harmonized World Soil Database v2.0 supports modelling, agroecological assessments, and analyses related to food security, land management, and climate change impacts.

43 Exceeding 230,000 entries from the FAO's World Soil Information Service (WoSIS) database (Ribeiro et al. 2018; https://www.isric.org/explore/wosis/faq-wosis).

44 Although its spatial resolution and generalized mapping structure reflected the limitations of available datasets at the time, it represented a major advance in global soil data harmonization and accessibility.

The Global Soil Information System

The Global Soil Information System (GloSIS), formally developed under the FAO's GSP in 2017, represents a more recent global effort, focusing on the harmonization of existing national and regional soil datasets, rather than the creation of a single centralized database. Unlike LUCAS, which is based on standardized primary data collection, GloSIS compiles and integrates existing data through the International Network of Soil Information Institutions.

Harmonization is achieved through internationally agreed standards[45]. Datasets are converted into a unified structure with variable units, consistent depth intervals, detailed metadata, and geospatial integration[46], supported by quality control procedures[47]. The resulting georeferenced data are integrated into interoperable platforms such as the GloSIS Portal, enabling the integration with global datasets on land cover, climate, and Remote Sensing. The decentralized, open-access spatial framework allows cross-country comparisons and global-scale assessments for research and policy applications. In this way, GloSIS reflects the broader shift from static databases towards dynamic and continuously evolving soil information ecosystems.

3.3.3. Phase 3: Integrated soil health monitoring and digital soil ecosystems (2019–Present)

Phase 3 is characterized by the transition from harmonized soil information systems towards fully integrated soil health monitoring ecosystems that directly support policy implementation, reporting, and adaptive governance. Driven by the European Green Deal, the EU Soil Strategy for 2030, Mission Soil, and the SMRD, this period places soil health at the centre of environmental policy. Advances in Earth Observation, digital soil mapping, AI, cloud computing, and FAIR data infrastructures have enabled the integration of observations, models, and decision-support tools within interconnected digital ecosystems. As a result, soil information is increasingly transformed from a static knowledge resource into an operational component of monitoring, forecasting, and evidence-based decision-making.

3.3.3.1. Characteristics of the 'Soil health' era

The launch of the European Green Deal (see section 2.2.5) in 2019 marked a decisive shift toward integrated and outcome-oriented soil governance. Soil was increasingly recognized as a strategic natural asset, underpinning climate neutrality, biodiversity conservation, and sustainable food systems. This reframing significantly increased the demand for robust, harmonised, and policy-relevant soil data.

Under this new governance paradigm, soil monitoring became a central component of policy implementation and accountability. The EU Soil Strategy for 2030 (see section 2.2.5.5) introduced the concept of soil health as a unifying framework for soil protection and restoration, supported by operational indicators capturing the physical, chemical, and biological condition of soils. The 'State

45 Including the GSP Pillar 5 guidelines, the FAO Global Soil Laboratory Network (GLOSOLAN) protocols, and alignment with the WRB classification system.

46 Coordinate system assignment.

47 Quality assurance is ensured through statistical checks for outliers and internal consistency, and methodological harmonization

of Soils in Europe 2024' Report (Arias-Navarro et al. 2024) further highlighted the multiple pressures affecting European soils and reinforced the need for integrated monitoring systems, capable of linking observations, modelling, and policy assessment.

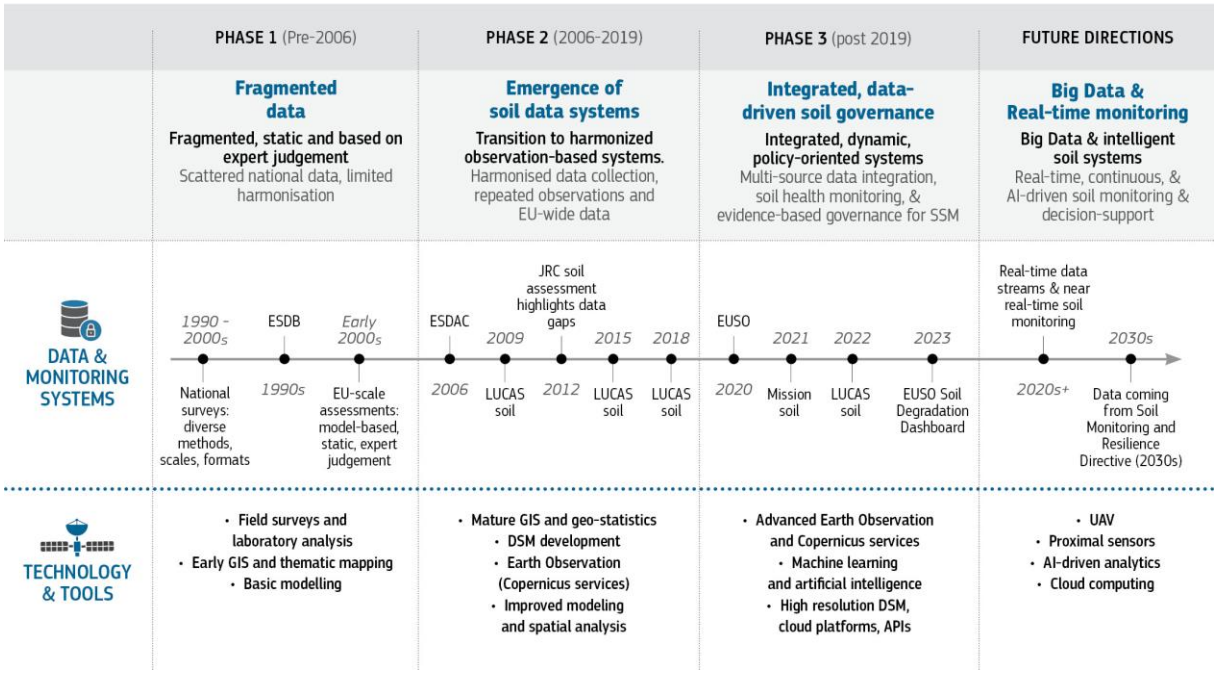
These policy developments were accompanied by major advances in data infrastructure and monitoring capabilities. The LUCAS Soil survey expanded through repeated sampling campaigns[48] (2009, 2015, 2018, 2022, etc.), a broader set of indicators and extended coverage, enabling the systematic detection of temporal changes in soil properties (see Chapter 4). At the same time, advances in Earth Observation – particularly through the Copernicus programme – expanded the use of Remote Sensing in soil-related applications. While direct soil measurements from satellites remained limited, Remote Sensing became essential for land use/land cover (LULC) dynamics (e.g. land take assessment), vegetation proxies linked to soil condition, soil moisture monitoring, soil erosion, etc. Modelling approaches also matured through higher spatial resolution, improved datasets, and enhanced validation procedures. This led to a gradual convergence between models and observations, reducing uncertainty.

The establishment of the EUSO in 2021 consolidated many of these developments by providing a central platform for the integration, analysis, and dissemination of soil information. Simultaneously, the SMRD formalises this transformation by introducing harmonised monitoring requirements, common indicators, standards for laboratory analysis, and reporting obligations across MS, strengthening the links between knowledge production, monitoring, and governance. Projects funded under the Mission Soil – such as SoilWise (3.3.3.2) – accelerated this transformation by generating new datasets, knowledge, and tools for soil monitoring by combining conventional soil survey methods with emerging data sources such as Remote Sensing, proximal sensing, and citizen science (Broothaerts et al. 2026). As a result, project outputs – all shared according to the FAIR principles – represent an important source of information, contributing to more cost-efficient and comprehensive soil R&I landscape.

Figure 8 illustrates the co-evolution of soil data infrastructures, monitoring systems, and technological capabilities across the three phases described in this chapter. The timeline highlights the progressive transition from static, expert-based soil information toward dynamic systems combining in situ observations, Earth Observation, and digital soil mapping approaches. The dashed extension indicates emerging trends associated with big data analytics, AI, and near real-time monitoring. This progression provides the foundation for the emergence of big data in soil science, which is discussed in detail in Chapter 3.3.4.

48 The early datasets marked a critical shift from model-based estimation toward observation-based assessment. Repeated sampling campaigns enabled, for the first time, the possibility of systematic trend detection rather than just mapping status.

Figure 8. Co-evolution of soil data systems and monitoring in the EU.



Source: JRC analysis.

3.3.3.2. Soil governance and monitoring platforms

The SoilWise Metadata Catalogue

A new generation of soil datasets is emerging through R&I initiatives funded under the Mission Soil. These projects are generating large volumes of soil data from various sources, including monitoring networks, Earth Observation platforms, proximal and remote sensing technologies, living laboratories, and citizen science activities.

The SoilWise project, developed under the Mission Soil, represents a new generation infrastructure, designed to address this persistent fragmentation of soil information across Europe. Conceived as an open-access knowledge and metadata repository, SoilWise aims to provide an integrated access point to heterogeneous soil datasets produced at local, national, and EU levels. Its primary objective is to ensure that soil information becomes FAIR, thereby enhancing discoverability, usability, and cross-domain integration. By connecting existing repositories – such as Zenodo, BonaRes, etc. – rather than replacing them, SoilWise strengthens the overall soil data ecosystem, improving interoperability and facilitating evidence-based decision-making in support of the EU Soil Strategy and the SMRD.

The platform incorporates metadata validation systems, transformation and harmonization services, and a soil knowledge graph that links datasets, indicators, and concepts across domains (Snopková et al. 2026). In addition, AI and Machine Learning techniques are employed to interlink disparate data sources, automate workflows, and generate new insights, thereby enhancing the overall 'FAIR-ness' and analytical value of soil data. Through its co-design approach involving researchers, policymakers, and land managers, SoilWise is positioned not merely as a metadata repository but as a long-term infrastructure supporting the evolution of the EUSO and the broader transition toward integrated, policy-driven soil information systems.

To this day, the transition from fragmentation to integrated, policy-driven systems remains incomplete. Significant challenges persist in relation to data accessibility, interoperability, and harmonisation across countries and institutions. Many soil datasets remain fragmented, unevenly distributed, or constrained by technical, institutional, and legal barriers that limit their integration and reuse. Differences in sampling designs, analytical methods, and data standards continue to affect comparability, while issues related to data ownership, licensing, and governance restrict wider data sharing. As a result, despite substantial progress, the shift from static datasets toward fully dynamic, multi-source information systems is still ongoing, and the potential of soil data as a strategic resource for scientific analysis, environmental assessment, and decision-support has yet to be fully realized.

3.3.4. Big data in soil science: sources, processing, and current challenges

In the modern digital age, soil-related information is increasingly generated as Big Data, characterized by three[49] primary dimensions (3Vs) – volume, velocity, variety (Goodchild 2016) – alongside continuous data streams (Hashem et al. 2015; Schade 2015). These data originate from diverse technologies, including Remote Sensing (Efthimiou et al. 2020; Alexiou et al. 2023), Unmanned Aerial Vehicles (UAVs[50]) (Peter et al. 2014; Neugirg et al. 2016), proximal sensing[51] (Viscarra Rossel et al. 2011) – including smart farming (Faulkner and Cebul 2014) and precision agriculture[52] (Wolfert et al. 2017) – Machine Learning (Wadoux et al. 2020), AI (Jain and Sethia 2023), spectroscopy (Rinnan and Rinnan 2007; Zornoza et al. 2008), and citizen science (Crall et al. 2010; Larson et al. 2020) (**Figure 9**). The evolution, capabilities, and applications of these technologies in soil monitoring are examined in detail in Chapter 4.

49 In addition to the original three Vs, a fourth dimension – veracity – has been introduced in the definition of big data (Schade 2015). Veracity refers not only to data quality, but also to the trustworthiness of the data sources and the robustness of the analytical methods applied. Ensuring veracity is essential for validating big data and enabling its accurate interpretation.

50 Local scale, i.e., landscape, field, etc., applications.

51 Using sensors.

52 While precision agriculture primarily focuses on managing spatial variability within fields, smart farming extends this by integrating real-time data streams, automation, and context-aware decision-making across the farm system.

Figure 9. Big Data sources in soil science.



Source: JRC analysis.

The rapid expansion of soil-related Big Data is driven by a combination of technological and socio-economic factors. On the one hand, push[53] factors involve innovations that enable continuous production, advanced processing, and analysis of vast environmental datasets. On the other hand, pull[54] factors reflect the increasing demand for evidence-based decision-making, cost-efficiency, and policy support, particularly in contexts such as food security, food safety and nutrition, climate change adaptation, and sustainable land management (Chen et al. 2014; Poppe et al. 2015; Tong et al. 2015). This push–pull dynamic accelerates the transition towards data-driven soil governance.

Within this framework, the Big Data chain[55] (**Figure 10**) represents the sequence of processes from data acquisition and storage to analysis, decision-making, and exploitation[56] (Chen et al. 2014; Miller and Mork 2013; OECD 2019). This chain highlights the transformation of raw data (and metadata) into actionable knowledge. Big Data analytics (de Mauro et al. 2016; Vassakis et al. 2018) thus has emerged as a paradigm to uncover patterns and relationships within complex, multi-source datasets. This is exemplified by the work of the ESDAC (Panagos et al. 2022b), which leverages large-scale soil datasets in support of both EU initiatives (Mission Soil, European Green Deal, etc.) and global targets (SDGs, LDN target, etc.).

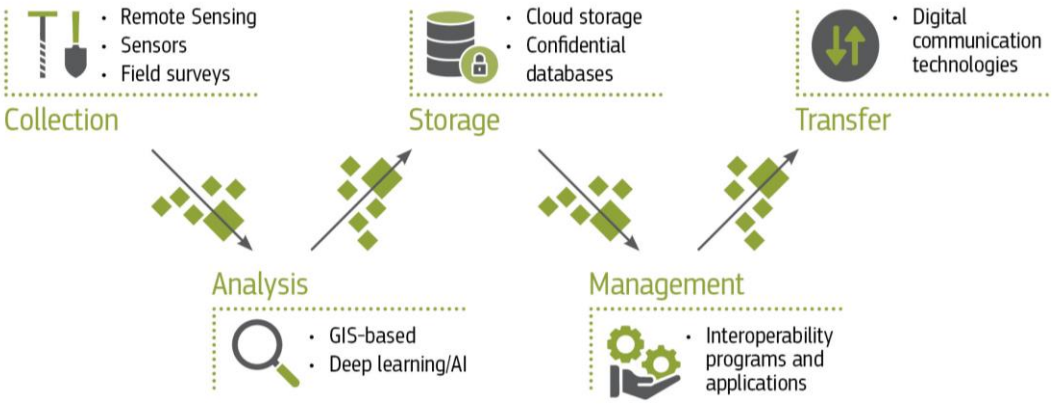
53 Because emerging technologies enable actors to attain higher-level or previously unattainable goals.

54 Because achieving certain goals requires new technological solutions.

55 The chain comprises two interconnected components: a technical layer that captures and processes raw data into usable information, and a business layer that uses this information to support decision-making and generate value through data-driven services. These layers interact across all stages, jointly forming what is known as the data value chain (https://www.ibm.com/think/topics/big-data).

56 Refers to the processes through which data are transformed into economic or societal value, including the provision of data-driven services, decision-support tools, and value-added products.

Figure 10. The chain of Big Data applications.



Source: JRC analysis.

A key challenge in contemporary soil mapping is the effective integration and exploitation of heterogeneous data sources, which reduces reliance on conventional field sampling that is often costly and time-consuming. Addressing this requires tackling technical issues in geo-processing soil Big Data (Liakos and Panagos 2022), including reproducibility[57], harmonization[58], compositing[59], zoning[60], aggregating results across scales (Miller and Schaetzl 2016), georeferenced mapping[61], plotting outputs[62], indicator development (Panagos et al. 2020), and uncertainty quantification[63] (Yan et al. 2015; Marin and Mattos 2020). Equally important is the collaboration model among scientists and stakeholders, increasingly facilitated by remote access, teleworking, and multi-source sharing.

57 Refers to the ability to repeat a study under the same conditions – using identical data, software, and code – and obtain consistent results (Gandrud 2015; Brunsdon and Comber 2021). The importance of reproducibility is further heightened in the context of big data, where complex requirements for data management, pre-processing, and analysis demand structured workflows capable of consistently reproducing results, even as data and standards evolve in near real time (Waller and Miller 2016; Yenni et al. 2019).

58 Involves transforming heterogeneous datasets into a unified and compatible format, enabling their comparability (Kumar et al. 2020). Over time, various techniques have been developed to support harmonization in big data contexts (Kumar et al. 2021). Advances in merging methodologies, scale integration, and the handling of heterogeneity in Remote Sensing data have further enabled data fusion at a global level (Longbotham et al. 2018). In Europe, harmonization frameworks for geospatial data have been aligned with the INSPIRE Directive (https://knowledge-base.inspire.ec.europa.eu/index_en), while more specialized approaches have been developed specifically for soil data at both global (Batjes et al. 2017; Ribeiro et al. 2018) and EU scales (Orgiazzi et al. 2018).

59 Merging high-resolution data into a single dataset (Zhang et al. 2018).

60 Representing and associating statistics zonally.

61 In the EU the most appropriate reference system for the study of soil-related spatial phenomena is the European Terrestrial Reference System 89 (ETRS89). ETRS89 is selected for being suitable for mapping at all scales and for the preservation of distances and areas (Bruyninx et al. 2015).

62 E.g. pie charts, donut charts, box plots, intricate maps, etc. This type of visualization communicates better the numeric results.

63 Commonly, by using the Monte Carlo method, which represents one or more variables as probability distributions. It then generates a large number of random samples from these distributions, producing a range of outcomes that collectively form a probability distribution and quantify the uncertainty of the variable (Kwak and Ingall 2007).

The application of AI and Machine Learning for gap filling, predictive modelling, and uncertainty assessment further depends on coordinated stakeholder networks. Beyond formal institutions (JRC, IUSS, FAO, etc.), these networks include technology providers, private companies, research organizations, and venture capital actors (Faulkner and Cebul 2014; Wolfert et al. 2017). Stakeholders differ in their capacity to generate, access, and process data, creating a dynamic landscape of collaboration, competition, and influence. Understanding these relationships is critical for adoption, interoperability, and effective policy implementation. Moreover, as the number of data users grows, the reciprocal value of Big Data increases, generating new insights and reinforcing the benefits of shared information (van 't Spijker 2014).

Despite strong technological drivers and clear policy demand, the under-exploitation of available data remains a major constraint within EU frameworks. For example, an ECA (2022) audit covering the period 2015-2022, reported that the CAP generates vast volumes of data through the Integrated Administration and Control System, the Land Parcel Identification System, and other sources[64]; however, these datasets are not systematically exploited for policy evaluation. Key constraints include fragmentation across MS, limited interoperability, restricted accessibility, and the absence of a coherent data governance strategy at EU level. Consequently, advanced (Big Data) analytics, multi-source integration, and AI/ Machine Learning applications remain underutilised, limiting the ability to establish robust cause–effect relationships between agricultural practices and soil-related outcomes, such as erosion dynamics, SOC changes, and broader land degradation processes.

3.4. Towards open and integrated soil data systems: challenges, requirements, and outlook

Over the coming decades, soil information systems are expected to evolve from fragmented and static datasets into dynamic, interoperable infrastructures capable of supporting climate resilience, sustainable soil management, and evidence-based policy. This transition is already being accelerated by a new generation of soil datasets emerging from research and innovation initiatives, particularly those funded under Mission Soil. These projects are generating large volumes of soil data from monitoring networks, Earth Observation platforms, proximal and remote sensing technologies, living laboratories, and citizen science activities, thereby expanding both the quantity and diversity of soil information available for monitoring and decision-making. However, realizing the full potential of these emerging data streams requires not only technological innovation but also systemic changes in data sharing, integration, and governance. While policy frameworks will play a key role, progress will depend equally on bottom-up scientific contributions and cross-sector collaboration.

A major constraint in advancing soil degradation assessments remains the lack of a standardized and comprehensive data sharing and integration policy. Soil data are often fragmented across institutions, countries, and research projects, frequently restricted by limited accessibility, inconsistent formats, and insufficient metadata. This fragmentation hampers a holistic understanding of soil degradation processes and their drivers. Addressing this challenge requires

64 Weather data, Earth Observation, surveys (e.g. farms' economic performance), environmental data (e.g. on biodiversity, soil quality), data collected through precision agriculture, data from mobile phone apps (e.g. on fertilizers, plant diseases), administrative data (e.g. market prices and payments), data on livestock movement.

the widespread adoption of the FAIR data principles (Wilkinson et al. 2016), alongside the development of open-access and trustworthy repositories aligned with the 'Transparency, Responsibility, User focus, Sustainability, and Technology' principles (Lin et al. 2020a). In addition, harmonized metadata standards and consistent methodologies are essential for enabling large-scale data integration and reuse (Hoffmann et al. 2020). Crucially, improved collaboration between data providers, aggregators, and users is needed to enhance both data availability and usability (Todd-Brown et al. 2022).

Beyond standardization, interoperability is a central requirement for future soil data systems. This includes not only technical interoperability – through standardized formats, web services, and Application Programming Interfaces – but also institutional coordination across sectors and governance levels. Importantly, soil data must increasingly be integrated with other environmental datasets, such as climate, hydrology, land use, and biodiversity, to support a more comprehensive assessment of soil ecosystem services and land degradation processes. Such interdisciplinary data exchange is fundamental for linking soil conditions with broader environmental and socio-economic dynamics.

Technological developments are rapidly enabling this transition. Advances in Earth Observation, proximal sensing, AI, and cloud computing allow the processing of large and heterogeneous datasets at unprecedented scales. In Europe, infrastructures such as the ESDAC are evolving toward more interactive and interoperable platforms, including web mapping services, enhanced user interfaces, and standardized Application Programming Interfaces to facilitate large-scale data access and integration (Schramm et al. 2021; Panagos et al. 2022b). These developments are aligned with international interoperability standards, e.g. the Open Geospatial Consortium (Kotsev et al. 2015; Trilles et al., 2017) and the INSPIRE Directive, enabling connections with major Earth Observation platforms such as Google Earth Engine and Open Data Cube (Soille et al. 2018; Gomes et al. 2020). The planned EU Soil Health Portal, as part of the SMRD, will further integrate data from national monitoring systems, Earth Observation, citizen science, and research projects, supporting a more comprehensive and continuously updated soil information system.

The increasing availability of high-frequency, harmonised soil data will provide a critical foundation for Early Warning Systems (see Ch. 4) embedded within future soil monitoring frameworks, enabling the detection of emerging risks and compound pressures across different soil threats.

Policy frameworks, including the SMRD, are expected to formalize requirements for soil data availability, quality, and reporting, effectively transforming soil information into a regulatory and strategic resource. However, a purely top-down approach is insufficient. Bottom-up initiatives, particularly research projects and monitoring networks, play a critical role in generating high-quality, innovative datasets and testing new methodologies. Open data practices within these initiatives – supported by platforms such as the ESDAC, SoilWise, and global repositories – can significantly enhance data availability and integration.

A balanced approach is therefore required, combining policy-driven coordination with bottom-up innovation. Emerging data sources, including citizen science and proximal sensing, can complement traditional surveys by increasing spatial and temporal data density. Ultimately, future soil information systems will rely on a tiered and interoperable architecture, integrating harmonized core indicators with context-specific data, supported by robust governance frameworks and advanced analytical tools. Such systems will enable soil data to become fully operational, decision-ready, and capable of addressing the complex challenges of soil degradation and sustainable land management.

3.5. Concluding remarks

The transformation of soil data systems in Europe illustrates how advances in digital infrastructure, data harmonisation, and open-access knowledge platforms have fundamentally reshaped the capacity to understand and manage soil resources. The progression from static soil inventories and fragmented national datasets toward interoperable, multi-source, and policy-oriented information systems marks a major scientific and institutional achievement. Platforms such as the EUSO have established the foundations of a European soil knowledge ecosystem capable of integrating field observations, remote sensing products, modelling outputs, and emerging big-data streams into coherent decision-support tools. This evolution has greatly enhanced the transparency, comparability, and usability of soil information for research, governance, and land management. At the same time, the rapid expansion of data sources introduces new challenges related to interoperability, uncertainty, quality assurance, and equitable access to digital capabilities. Moving forward, the value of soil data will increasingly depend not only on technical sophistication but also on the adoption of FAIR principles, robust governance frameworks, and stronger links between data generation and practical decision-making. In this context, soil data must be understood not merely as a scientific resource, but as critical infrastructure underpinning evidence-based policy and adaptive soil stewardship.

4. Changes in soil monitoring and new data sources

4.1. Introduction

Soil monitoring is a cornerstone of sustainable land management, providing the empirical basis for assessing soil health, understanding the impacts of land use and climate pressures, and evaluating the effectiveness of policy interventions aimed at soil protection and restoration. Given that soils underpin food security, climate regulation, biodiversity, ecosystem services, etc., monitoring systems are essential not only for scientific assessment but also for policy implementation, compliance, and long-term environmental governance. Reliable soil information enables the identification of degradation trends, supports early warning of emerging risks, and informs targeted restoration actions across diverse agroecosystems and landscapes. Over the past decades, soil monitoring in Europe has undergone a profound transformation, evolving in response to technological advances, policy needs, and increasing environmental pressures.

At the same time, it is important to recognise that soil monitoring is not a single, uniform activity, but rather encompasses a spectrum of approaches that vary according to scale, purpose, and end-users. As highlighted by Campbell et al. (2025), monitoring systems can range from extensive statistical surveys and long-term experimental sites to high-resolution sensor networks and Remote Sensing-based assessments, each serving different objectives – from national reporting and policy evaluation to farm-level decision-making. This diversity underscores the need for integrated frameworks capable of combining multiple data sources and methodologies into coherent and policy-relevant monitoring systems.

Traditionally, soil monitoring in Europe relied on field-based surveys, underpinned by conceptual frameworks and expert-driven assessments. Legacy indicator-based programmes and composite indices have played an important role in establishing baseline assessments of soil health risk; however, their dependence on fixed indicators and static weighting schemes often limits their ability to capture short-term dynamics. In addition, their effectiveness is constrained by the scarcity of reliable observations – particularly those of high temporal resolution (e.g. sub-daily) and broad spatial coverage (e.g. beyond plot scale) – as well as delays in data acquisition, the lack of harmonised and standardised soil datasets, and the high cost, time consumption, and effort associated with conventional monitoring approaches. These limitations underscored the need to adopt more efficient and adaptive methods for data acquisition.

In recent years, however, a wide range of emerging data sources and technologies – including Earth Observation (Eltner et al. 2015; Efthimiou et al. 2020), proximal sensing (Viscarra Rossel et al. 2017; Babaeian et al. 2019), soil spectroscopy (Zornoza et al. 2008; Stevens et al. 2013), etc. – have significantly expanded monitoring capabilities (Broothaerts et al. 2026). These approaches enable the assessment of soil properties, soil degradation processes, and their drivers at unprecedented spatial and temporal scales. When combined with established datasets such as LUCAS Soil and complemented by citizen science initiatives, they offer the potential for more comprehensive, efficient, and cost-effective soil health assessments.

From a policy perspective, these developments are particularly relevant, as sensor-based and model-derived data can contribute directly to monitoring the soil descriptors defined under the SMRD and the indicators included in the EU Mission Soil Implementation Plan (Broothaerts et al. 2026). However, the integration of diverse data streams remains challenging, requiring i) harmonisation of methodologies, ii) alignment of spatial and temporal scales, and iii) reconciliation

of direct measurements with indirect proxies of soil properties and processes. Moreover, not all soil properties can yet be reliably measured using modern techniques.

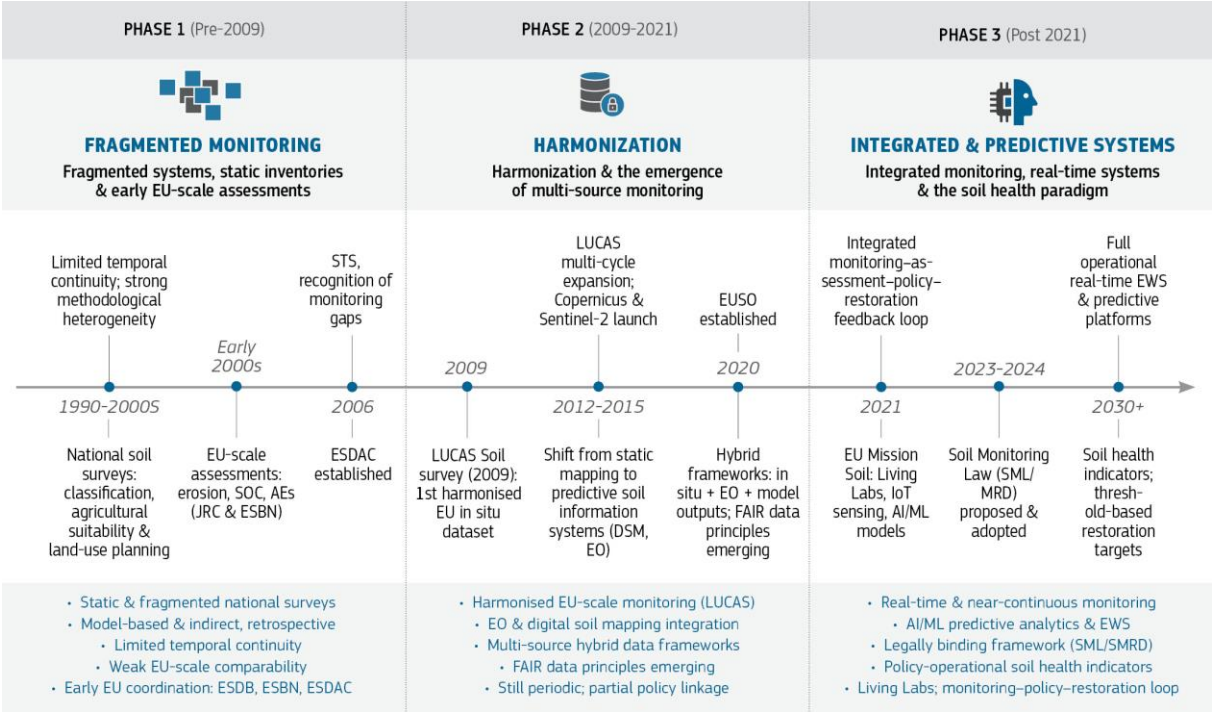
Against this background, the main objective of this chapter is to analyse the evolution of soil monitoring in the EU, with a particular focus on the transition toward integrated, multi-source, and policy-oriented systems. The chapter (i) examines the historical development of soil monitoring across three key phases, (ii) analyses the emergence and integration of new data sources and technologies, and (iii) evaluates current challenges and future directions, including the role of EU policy frameworks and innovation initiatives in shaping next-generation monitoring systems

By bridging scientific, technological, and policy perspectives, the chapter aims to provide a comprehensive understanding of how soil monitoring can support effective soil governance and sustainable land management in Europe.

4.2. Evolution of soil monitoring in the EU

The evolution of soil monitoring in the EU reflects not a single linear process, but the co-evolution of multiple interacting domains, including scientific knowledge, technological innovation, environmental pressures, socio-economic demands, and policy development. Before 2009, soil monitoring systems developed in a fragmented manner, largely confined within national boundaries and designed for agricultural or land evaluation purposes. Over the past decades, however, the increasing recognition of soil as a critical natural resource – supporting food production, climate regulation, biodiversity, water systems, etc. – has driven the transition toward more integrated, harmonised, and data-driven monitoring frameworks. In this section, the main phases of soil monitoring in the EU over the past decades will be discussed. These phases are summarised in (**Figure 11**).

Figure 11. Evolution of soil monitoring in the EU: from fragmented surveys to integrated, data-driven systems.



Source: JRC analysis.

4.2.1. Phase 1 (pre-2009): Fragmented systems, static inventories, and early EU-scale assessments

Prior to 2009, soil monitoring in Europe was characterised by fragmentation, static knowledge bases, and limited spatial coverage. Since the 1950s, most MS developed national soil survey programmes, primarily targeting soil classification, agricultural suitability, and land-use planning (Arrouays et al. 2008; Huber et al. 2008; Morvan et al. 2008; van Leeuwen et al. 2017; Bispo et al. 2021; Arias-Navarro et al. 2024). These surveys generated valuable information and extensive datasets on soil physical and chemical properties. However, they did not capture temporal changes in these properties, nor did they address ecosystem services, soil functions, or soil degradation. This resulted in i) limited temporal continuity, ii) strong methodological heterogeneity, and iii) weak comparability at the European scale.

At the EU level, early coordination efforts – most notably the establishment of the European Soil Database and the European Soil Bureau Network – represented important steps toward harmonisation. However, these initiatives remained largely focused on static soil attributes, rather than monitoring dynamic soil processes.

The early 2000s introduced a gradual shift toward process-oriented assessments, supported by advances in geospatial modelling and the growing role of the JRC. During this period, the first continental-scale assessments of soil degradation, including soil erosion (van der Knijff et al. 2000; Kirkby et al. 2004) and SOC dynamics (Jones et al. 2005a; Smith et al. 2005), were developed. At the same time, the introduction of AEI (Gobin et al. 2004; Yli-Viikari et al. 2007) and GAEC under the CAP marked an initial attempt to link soil monitoring with policy evaluation frameworks.

A key milestone in this phase was the establishment of the ESDAC in 2006 (Panagos et al 2022b; https://esdac.jrc.ec.europa.eu/see section 3.3.2.2), which began consolidating dispersed datasets into a more structured European platform. Nevertheless, monitoring remained i) largely model-based and indirect, ii) dependent on limited and non-systematic field observations, and iii) primarily retrospective and periodic (rather than continuous) (Vleeshouwers and Verhagen 2002; Jones et al. 2005a; Smith et al. 2005; Morvan et al. 2008; Saby et al. 2008)[65]. Technological constraints further limited progress, as monitoring relied heavily on field sampling and conventional mapping, with restricted capacity to capture spatial variability or temporal change at scale.

The adoption of the STS in 2006 (see section 2.2.2) represented a turning point, explicitly recognising the lack of harmonised soil data as a key barrier to effective soil governance. Although the proposed Soil Framework Directive was not adopted, this period led to significant progress in the institutionalisation of soil data systems.

An important milestone in the development of a harmonised European soil monitoring framework was the ENVASSO (Environmental Assessment of Soil for Monitoring) project, funded under the European Commission's Sixth Framework Programme (2006–2008). The project reviewed existing soil inventories and monitoring networks across MS, evaluated nearly 300 potential indicators, and identified a core set of indicators and protocols for assessing major soil threats, including erosion,

65 The work of Vleeshouwers and Verhagen (2002) and Smith et al. (2005) exemplifies the model-based nature of assessments; the work of Vleeshouwers and Verhagen (2002) and Jones et al. (2005) exemplifies indirect/indicator-based approaches; and the work of Morvan et al. 2008) and Saby et al. (2008) directly documents the absence of systematic field observations at continental scale prior to the LUCAS soil survey (first conducted in 2009).

organic matter decline, contamination, compaction, salinisation, soil sealing, biodiversity loss, landslides, and desertification. ENVASSO also proposed a framework for a European soil monitoring system, including harmonised sampling procedures, data management approaches, and a tiered monitoring strategy based on indicator relevance and feasibility.

At the same time, growing awareness of the environmental and economic impacts of soil degradation strengthened the demand for more reliable and comparable soil information across MS.

4.2.2. Phase 2 (2009-2021): Harmonisation and the emergence of multi-source monitoring

The period after 2009 marks a turning point toward harmonised, EU-wide soil monitoring, with the launch and expansion of the LUCAS programme acting as a critical boundary. For the first time, Europe obtained a systematic, harmonised, and periodically updated in situ soil dataset, significantly improving data comparability across MS. This phase is characterised by three major transformations, namely i) harmonisation and improved EU-scale assessments, ii) emergence of Earth Observation and digital soil mapping, and iii) Integration of multi-source data systems.

With respect to harmonisation, the availability of LUCAS data enabled more robust and comparable pan-European assessments of soil conditions and trends, e.g. for SOC (Nocita et al. 2013; Panagos et al. 2013b; Stevens et al. 2013; Lugato et al. 2014; de Brogniez et al. 2015), soil contamination (Ballabio et al. 2018, 2021, 2024; Fendrich et al. 2024), etc. This substantially reduced uncertainties associated with earlier model-based approaches.

Rapid advances in Earth Observation – especially through the Copernicus programme – introduced consistent, high-resolution, and frequently updated spatial data streams. Indicators such as soil moisture and soil sealing were genuinely measured or detected by Earth Observation sensors. Erosion (Panagos et al. 2014b, 2020) and soil organic matter, by contrast, were modelled using EO-derived inputs (land cover, vegetation indices, spectral reflectance composites). Additional indicators include soil salinity (Daliakopoulos et al. 2016) and soil physical properties (Ballabio et al. 2016). It is noteworthy that EO-based soil biodiversity monitoring is essentially non-existent in this period, and assessments relied on proxies (Gardi et al. 2013; Orgiazzi et al. 2016a). These developments were complemented by Digital Soil Mapping techniques (Minasny and McBratney 2016), cloud computing, and the increasing use of geo-statistics and Machine Learning (Wadoux et al. 2020). Together, these innovations further enhanced analytical capacity, enabling the transition from static mapping to spatially explicit, predictive models, Early Warning Systems, and laying the groundwork for near real-time soil monitoring frameworks (see section 4.2.3).

On the integration front, soil monitoring evolved toward hybrid frameworks, combining in situ observations (e.g. LUCAS), satellite data, and model outputs (d'Andrimont et al 2021; van Wesemael et al. 2024). Although still not fully integrated, this marked the beginning of a connected soil data ecosystem. At the same time, principles of data interoperability and FAIR data management (Wilkinson et al. 2016) started to gain traction. Despite these advances, limitations persisted. Monitoring systems remained partly fragmented across thematic domains, still periodic rather than continuous, and only partially integrated into decision-support and policy implementation frameworks. Data interoperability remained a recognised bottleneck. A notable lack of coherent data collection and analysis practices was observed, including different data standards, different data accessibility, and lack of interoperability – an issue manifested in practice by the slow availability of data, such as the LUCAS 2015 campaign data that were released only in 2020 (van

Wesemael et al. 2023). A further, technically concrete barrier to EO–in situ integration was the fundamental spatial mismatch between the LUCAS point observation footprint and Earth Observation sensor resolutions[66] (d'Andrimont et al. 2021).

Broadly, the landmark decision by Copernicus to make Sentinel images freely available fostered quick advancements in the analysis of Earth Observation big data for long-term and large-scale digital soil mapping applications (Tziolas et al. 2021), but the review community noted that pilot applications were mainly restricted to relatively small areas, with only a few samples, limiting the scalability of Earth Observation soil solutions to new geographical areas (Tziolas et al. 2021).

4.2.2.1. The Land Use-Land Cover Area-Frame Survey (LUCAS)

A prominent example of a harmonized soil data infrastructure is the EU-wide LUCAS soil database (Tóth et al. 2013a; Orgiazzi et al. 2018), managed by the JRC. This continent-scale initiative applies a harmonized sampling framework on a regular, tri-annual basis, combined with strict field protocols[67] and controlled laboratory analyses[68] to generate high-quality comparable topsoil (0–30 cm) data across MS (Orgiazzi et al. 2018).

The dataset includes a wide range of physical and chemical parameters, such as coarse material (%), granulometry (%), SOC (%), surface stone cover (%), nutrients, pH, etc., and increasingly incorporates microbiological properties (Orgiazzi et al. 2022). Despite some limitations in data coverage (Zhang et al. 2017), the systematic spatial distribution of sampling points across the EU, ensures statistically representative coverage of major land-use types, making LUCAS one of the most consistent soil datasets available at continental scale.

A key strength of LUCAS lies in its harmonization approach, which ensures consistency in sampling design, analytical methods, and data structure. This enables cross-border comparability and supports the integration of soil data into EU-wide assessments and modelling frameworks. In this context, LUCAS provides essential input (ground-truth) data for model calibration and validation (Poesen 2018) in, e.g. soil erosion[69] (Nearing 2000); land degradation; productivity assessment; Early Warning Systems; Machine Learning applications. Furthermore, it increases the predictive ability and accuracy of digital soil maps – such as SoilGrids – through benchmarking (Minasny and

66 The standard LUCAS core protocol was designed for land-use statistics, not Remote Sensing calibration: each observation corresponds to a circular area of approximately 7 m^2 radius, while a single Sentinel-2 pixel covers 100 m^2 - a single pixel may therefore span multiple LULC types, none of which is fully captured by the LUCAS point. This geometric incompatibility rendered the LUCAS core observations unsuitable for direct use in training and validating EO-derived soil and land cover products (d'Andrimont et al. 2021). A dedicated solution was only introduced with the 2018 survey round, in the form of the LUCAS Copernicus module – a new protocol specifically designed to record the homogeneous and continuous land cover extent up to 51 m in four cardinal directions around each observation point, thereby generating polygon-based in situ data geometrically compatible with decametric sensors such as Sentinel-1 and Sentinel-2. Critically, however, even this purpose-built dataset had seen only marginal uptake by the Earth Observation community at the time of its formal publication in 2021, underlining how slowly the structural gap between in situ survey design and Earth Observation integration requirements was being closed (d'Andrimont et al. 2021).

67 Including standardized procedures for site selection, sample extraction, geo-referencing, and in situ observations (e.g. LULC, management practices, erosion signs).

68 Conducted in a single ISO-certified laboratory (Cools et al. 2004), using harmonized methodologies which ensure internal consistency and minimizing analytical bias across survey years.

69 E.g. the LUCAS 2009-12 inputs enabled the modelling of both soil erodibility (Panagos et al. 2014a) and the soil's wind-erodible fraction (Borrelli et al. 2014) in the EU.

McBratney 2016). Beyond its role in modelling applications, LUCAS has also supported the development of EU soil indicators by providing harmonised field measurements required to define reference values, assess spatial variability, and evaluate temporal trends in soil properties (Broothaerts et al. 2024). This contribution has been particularly important for strengthening evidence-based soil monitoring and the implementation of EU soil policy frameworks.

LUCAS is fully georeferenced and interoperable with GIS, facilitating its integration with auxiliary spatial datasets, including climate variables, topography, land cover, biological properties, and Earth Observation products (e.g. Copernicus). As such, LUCAS plays a central role in advancing data standardization, interoperability, and accessibility within the European soil information landscape.

Beyond its role as data source, LUCAS constitutes a key component of the European soil monitoring system. Its iterative design, based on repeated survey campaigns (2009, 2012, 2015, 2018, and 2022), allows for the analysis of temporal changes in soil properties[70] across the EU, despite methodological challenges associated with ensuring comparability among different sampling rounds (**Figure 12**).

The initial LUCAS Soil module (2009) established the baseline for EU-wide topsoil characterization, focusing on fundamental physical and chemical properties, such as SOC, texture, pH, and nutrients (Tóth et al. 2013b). The 2012 campaign expanded the dataset, increasing the number of sampling points and refining laboratory protocols. The 2015 survey further improved spatial representativeness and introduced enhanced quality control procedures, supporting the development of Digital Soil Mapping products and large-scale environmental assessments (Fernández-Ugalde et al. 2020; Jones et al. 2020).

A major advancement was introduced in the 2018 survey, which incorporated additional variables[71] and the systematic visual assessment of soil erosion processes at approximately 26,000 sampling locations (Orgiazzi et al. 2018; Fernández-Ugalde et al. 2022). Records included erosion type (e.g. sheet, rill, gully, mass movement, re-deposition, wind erosion), along with its distance and direction from the sampling point and the number of rills or gullies observed. The visual assessment of gully erosion through LUCAS 400,000 observations allowed for the development of first assessment of gully erosion (Borrelli et al. 2025). This allowed for the integration of qualitative indicators – erosion type, intensity proxies, and spatial context – with quantitative soil measurements. This enriched the dataset's applicability for land degradation and soil conservation studies.

70 Physical properties (Ballabio et al. 2016), SOC (Nocita et al. 2013; Panagos et al. 2013b; Stevens et al. 2013; de Brogniez et al. 2015), other chemical properties (Ballabio et al. 2019), and concentrations of potentially toxic elements (Ballabio et al. 2018, 2021, 2024; van Eynde et al. 2023; Fendrich et al. 2024).

71 The 2018 LUCAS Soil Survey incorporated dedicated modules to assess soil biodiversity, pesticides, and microplastics (Orgiazzi et al. 2022). In addition to biodiversity, the pesticides module generated data from more than 3,400 sites – primarily in croplands and grasslands – analysing 118 active substances and their metabolites. Together, these datasets constitute one of the most extensive collections of soil biological and contamination information at the European scale, offering strong potential for the development of indicators and for supporting the monitoring of environmental and agricultural policies.

Figure 12. LUCAS soil sampling over the years (2009-2022).

LUCAS Soil Sampling over the years

	2009 - 2012	2015	2018	2022
Sampling points	19 000	23 000	26 000	36 000
Physico-chemical properties				
PSD: clay, silt, sand	✓	✓	✓	✓
pH (CaCl, HO)	✓	✓	✓	✓
Organic carbon	✓	✓	✓	✓
Carbonate content	✓	✓	✓	✓
Total nitrogen content	✓	✓	✓	✓
Potassium content	✓	✓	✓	✓
Phosphorous content	✓	✓	✓	✓
Cation exchange capacity	✓	✓	✓	✓
Electrical conductivity	■	✓	✓	✓
Metals	✓	■	✓	✓
Multispectral properties	✓	✓	■	✓
Mineralogy	✓	✓	■	■
Soil biodiversity (DNA)				
Bacteria (16S)	■	■	✓	✓
Fungi (ITS)	■	■	✓	✓
Eukaryotes (18S)	■	■	✓	✓
Metagenomics	■	■	✓	✓
Bulk density				
Bulk density	■	■	✓	✓
Soil moisture	■	■	✓	✓
Field measurements				
Soil erosion	■	■	✓	✓
Thickness of organic layer	■	■	✓	■
Pollution				
Pesticides residues	■	■	✓	✓
Antibiotics				
Polypeptide antibiotics	■	■	✓	■
Fluoroquinolone antibiotics	■	■	✓	■

■ analysis not performed ✓ analysis performed

Source: JRC analysis.

The 2022 campaign has further expanded the analytical scope to include emerging soil health indicators, particularly biological properties and spectroscopic measurements, reflecting the growing emphasis of soil biodiversity and ecosystem functioning within EU policy frameworks (Orgiazzi et al. 2022). For example, the number of sampling sites dedicated to soil biodiversity measurements has been increased to 2,000, effectively doubling the coverage (Panagos et al. 2022b).

Through its temporal consistency and standardized methodology, LUCAS supports:

- The development of policy-relevant indicators that capture how management practices influence soil properties (Orgiazzi et al. 2018).
- The systematic observation and trend analysis of soil properties over time
- The evaluation of policy impacts under frameworks such as the EU Soil Strategy, the European Green Deal, and LDN targets

Overall, the LUCAS soil dataset represents a cornerstone of European soil information landscape, combining harmonization, continuity, transparency[72] and accessibility. Its constant evolution and expanding scope valorise it as a critical tool for bridging the gap between scientific research and policy implementation.

4.2.2.2. Proximal sensing

Terrestrial Laser Scanning (TLS)

TLS, a ground-based Light Detection and Ranging technique, is an advanced surface mapping method capable of producing high-resolution three-dimensional topographic data at mm- to cm-scale accuracy across multiple spatial scales. It enables rapid and non-invasive measurements (Stenberg et al. 2016) and is particularly effective in mapping inaccessible or complex terrain (Fey and Wichmann 2017). As such, TLS has been widely applied in environmental studies, including soil erosion assessment (Vinci et al. 2015), aeolian geomorphology (Nield et al. 2011), and mass movement investigations (Oppikofer et al. 2009).

In the context of soil health, TLS supports the detailed quantification of surface processes, such as changes in soil roughness in semi-arid rangelands, the seasonal evolution of gullies, and the detection of wind erosion in dryland environments (Eitel et al. 2016). Moreover, its high spatial accuracy makes it particularly suitable for providing ground reference data for the calibration and validation of erosion and land degradation models.

Despite these advantages, TLS applications are subject to several limitations. Terrain complexity can lead to data occlusion, especially in single-scan acquisitions (Becker et al. 2009). Reducing these gaps typically requires multiple scans from different positions, increasing field effort, data volume, and processing requirements (Yilmaz and Uysal 2016), and posing logistical challenges in rugged landscapes (Liang et al. 2012). Additional uncertainties arise from acquisition noise and scan alignment errors. Although multi-scan integration can mitigate occlusion effects, it often results in point clouds with variable densities, complicating the generation and analysis of Digital Elevation Models (DEMs) (Goodwin et al. 2016).

72 The dataset is made openly available through the EC JRC data infrastructure.

Overall, TLS represents a powerful proximal sensing technique for high-resolution analysis of soil surface dynamics. While its application is generally limited to plot- to hillslope-scale investigations, it plays a critical role in supporting process-based understanding and model validation within modern soil monitoring frameworks.

Field spectroscopy

The fundamental principle of soil spectroscopy is the interaction between electromagnetic radiation and the soil sample or exposed ground surface (Broothaerts et al. 2026). This interaction may involve processes such as absorption, fluorescence, emission, or diffraction, resulting in a distinctive spectral signature of the soil. Measurements can be acquired using benchtop and handheld spectrometers, or satellite-based sensors.

Spectroscopy has the potential to generate soil datasets with higher spatial and temporal resolution at lower cost compared to conventional laboratory analyses (O' Rourke and Holden 2011; Li et al. 2022). This is achieved by calibrating spectral measurements against reference data obtained through standard analytical techniques, such as dry combustion for determining total carbon content. Once established, these calibration regression models can be applied to estimate soil properties for additional samples using spectral data alone. A key component of this approach is the creation of spectral libraries[73], which consist of paired datasets combining analytical and spectroscopy measurements of the soil (Shepherd and Walsh 2002). Such libraries can be used to expand existing soil datasets, for instance by predicting larger datasets that only have spectral information (e.g. Breure et al. 2025).

Visible and near-infrared spectroscopy (VNIRS) represents the most widely established spectroscopic approach. The standardization of spectral measurements on a soil standard is a protocol step that can reduce intra-laboratory variability in spectral acquisition and improve the transferability of calibration models between spectral libraries developed under different protocols and instrumentation (Ben-Dor et al. 2015; Kopačková and Ben-Dor 2016; Gholizadeh et al. 2021). At the European scale, VNIRS has been progressively integrated into large-scale soil monitoring frameworks. It was applied in the LUCAS soil surveys of 2009 and 2015, yet without incorporating the standardization process. To address this limitation, the EUSO has introduced the use of international soil standards in the VNIRS measurements of the LUCAS 2022 survey. This work is particularly relevant in the context of the SMRD, where soil analyses will be conducted across laboratories in different MS. Given the relatively low replication error associated with VNIRS, future research may explore the extent to which spectral standardization can support the harmonisation of SMRD datasets, especially for soil properties with distinct spectral absorption features, such as SOC, $CaCO_3$, particle size distribution, and electrical conductivity.

While spectroscopy has traditionally focused on physical and chemical properties, recent research has begun to explore the potential of infra-red (IR) spectroscopy for assessing soil biological

73 The EUSO is collaborating with the WHEATWATCHER (https://wheatwatcher.eu/) and ECHO (https://echosoil.eu/) Mission Soil projects to investigate the development of a European-scale X-ray fluorescence spectral library based on samples from the LUCAS 2009 survey. X-ray fluorescence spectroscopy shows promise for the detection of heavy metals in soils, although challenges related to instrument standardization remain. Both projects utilise EURO-Soils standards (Kuhnt and Muntau 1994) developed by the JRC, enabling the evaluation of calibration transferability across different instruments. The outcomes of this work are expected to provide insights into the feasibility and added value of establishing a harmonised, EU-wide X-ray fluorescence spectral library for soil characterisation.

properties, although applications remain more limited compared to physical and chemical attributes (Kuang et al. 2012). Earlier studies demonstrated that IR spectra can be used to estimate microbial and enzyme activity, microbial biomass, nutrient contents, and phospholipid fatty acid biomarkers (e.g. Rinnan and Rinnan 2007; Zornoza et al. 2008). More recently, advances in omics approaches have opened new avenues for linking VNIR spectroscopy with soil microbial communities[74], with studies investigating its added value in predicting bacterial abundance beyond conventional soil properties (Yang et al. 2019).

In-situ sensors

Proximal sensing also involves the use of sensors positioned close to or in direct contact with the soil to measure its properties in situ (Viscarra Rossel et al. 2011). These networks enable the assessment of a wide range of physical, chemical, and biological parameters – e.g. soil moisture (Babaeian et al. 2019), nutrient content, SOC (Viscarra Rossel et al. 2017), texture – using optical, geophysical, electrochemical, and mechanical methods. Such technologies are widely used in precision agriculture (Wolfert et al. 2017) for optimizing crop management, as well as in soil health monitoring, and contamination assessment.

A key advantage of in-situ sensing is its ability to generate high-resolution data, supporting detailed soil mapping and near real-time monitoring. Overall, sensor-based data provide valuable insights into spatial soil variability, enabling farmers and land managers to implement targeted sustainable soil management practices. Typically, sensors operate at field to regional scales, although their outputs can, in some cases, be extrapolated using Remote Sensing data, depending on the survey design and methodology.

Despite the growing use of sensor technologies, significant potential remains untapped in leveraging sensor-derived data for comprehensive and cost-effective soil health monitoring (Broothaerts et al. 2026). In particular, the integration of sensor data with other data streams – such as traditional soil sampling surveys – remains relatively underexplored.

4.2.2.3. Remote sensing platforms

Satellites

Satellite imagery has significantly advanced geospatial analysis by enabling timely, cost-effective, and accurate data acquisition across large spatial extents. Compared to traditional field-based approaches, it provides multi-temporal and high-resolution observations at regional to global scales in a readily accessible format (Chen et al. 2016).

Beyond its established role in soil erosion research (Meusburger et al. 2010; Efthimiou et al. 2020), satellite-based Remote Sensing supports a wide range of environmental applications, including landslide susceptibility mapping (Psomiadis et al. 2020), hydrological monitoring (Psomiadis et al. 2019), etc. Major Earth Observation missions – such as MODIS, Landsat, and the Sentinel-2 programme developed by the European Space Agency within the Copernicus framework – have

74 The EUSO, in collaboration with the AI4SH (https://ai4soilhealth.eu/) and SOB4ES (https://www.sob4es.eu/) Mission Soil projects, is advancing experimental work by acquiring VNIR spectra for LUCAS 2018 soil biodiversity samples. These efforts aim to evaluate whether spectroscopy can enhance the characterization of soil biological properties, assess the transferability of calibration models across different contexts, and examine the implications of using predicted versus directly measured biological indicators.

significantly advanced the capacity to monitor environmental dynamics. These platforms enable detailed observation of vegetation dynamics, crop phenology, and LULC changes, including deforestation and urban expansion, while also supporting applications such as yield forecasting and flood mapping (Belgiu and Csillik 2018; Zoka et al. 2018).

The availability of high-temporal and high-spatial resolution datasets allows for the systematic monitoring of key biophysical indicators, e.g. Normalized Difference Vegetation Index, Soil Water Index, Surface Soil Moisture, etc., as well as land surface temperature and soil moisture. These indicators are critical for identifying land degradation hotspots, where early signs of soil health deterioration – such as declining vegetation vigour, increasing surface reflectance (albedo), etc. – are often subtle but progressively intensify over time (Prince et al. 2009; Vrieling 2006).

Despite its effectiveness at large spatial scales, Earth Observation has limitations in capturing subsurface soil properties and may be constrained by atmospheric conditions such as cloud cover. From a scientific perspective, key challenges relate to information limitations, including the degree to which surface characteristics can be accurately represented, the impact of cloud interference, scale mismatches, the lack of standardized or harmonised measurement frameworks (e.g. Zeng et al. 2025), and the fact that several soil properties can yet be (reliably) measured. In addition, the broader uptake of Earth Observation data is influenced by national capacities, such as the availability of Remote Sensing and soil expertise, as well as the technical skills of end users (Renault et al. 2024).

RS offers considerable potential for advancing soil monitoring in the future, particularly through improved spatial and temporal data coverage. However, further progress depends on addressing key limitations, including the development of standardized soil spectral libraries and the enhancement of data accessibility for non-specialist users. Expanding usability is essential to foster broader adoption and maximise the benefits of Earth Observation technologies. At the same time, ethical considerations must be considered, as Earth Observation data may raise concerns related to privacy and data governance (Renault et al. 2024). Therefore, alongside technological advancements, careful attention is needed to ensure responsible and equitable use of Earth Observation in soil monitoring.

Unmanned Aerial Vehicles (UAVs)

At the local scale, UAV imagery effectively bridges the gap in spatial and temporal analysis between traditional field observations and data acquired from manned aircrafts (Aber et al. 2010) or satellite platforms. Their applications span multiple domains, including soil erosion monitoring (d'Oleire-Oltmanns et al. 2012; Eltner et al. 2015), environmental monitoring (Manfreda et al. 2018), landslide mapping (Lucieer et al. 2013), and post-flood assessment (Andreadakis et al. 2020).

In the context of soil health assessment, UAVs equipped with multispectral or hyperspectral sensors enable the estimation of key soil properties, including moisture content, organic matter, nutrient status, and texture. These data provide valuable insights into soil variability, supporting more targeted and efficient land management practices. When integrated with precision agriculture technologies, UAV-derived information allows for optimized application of inputs such as water, fertilizers, and pesticides, thereby enhancing soil health while reducing environmental impacts and costs (Broothaerts et al. 2026).

The increasing use of UAV-based Remote Sensing is driven by several practical and technological advantages, including the ability to acquire high-resolution data with dense spatial coverage in a cost- and time-efficient manner. UAVs offer flexible and repeatable mission planning, enabling

frequent monitoring and user-defined data acquisition. Their lightweight and non-invasive nature allows for rapid deployment while preserving site integrity, making them particularly suitable for surveying inaccessible or hazardous areas such as steep or unstable terrain. In addition, the growing availability of affordable data processing and reconstruction software has further expanded their applicability in geospatial analysis (Aber et al. 2010).

Airborne laser scanning

Airborne laser scanning systems, typically mounted on aircraft or UAVs, provide substantially broader spatial coverage than TLS, albeit at dm- to m-scale resolution. This makes these systems particularly suitable for landscape- to regional-scale applications. Compared to TLS, Airborne Laser Scanning is more effective for monitoring large-scale landform dynamics and erosion patterns (Eitel et al. 2016), and it enables spatial extrapolation as well as integration into regional soil monitoring frameworks, whereas TLS is primarily suited for high-precision ground truthing.

Airborne Laser Scanning has been successfully applied across a wide range of environmental domains, including forest biomass estimation (Zhao et al. 2009), biodiversity monitoring (Laurin et al. 2016; Bouvier et al. 2017), and vegetation degradation assessment (Kaminska et al. 2018). Despite these advantages, airborne surveys remain relatively costly and are not universally accessible, particularly in resource-limited regions. In addition, they involve significant technical and computational demands in both data acquisition and processing (Wulder et al. 2012).

4.2.3. Phase 3: Integrated monitoring, real-time systems, and the soil health paradigm (2021–present)

Since 2021, soil monitoring in Europe has entered a new phase defined by integration, operationalisation, and policy embedding, driven by both technological maturity and strong policy momentum.

A central milestone is the launch of the Mission Soil (see section 2.2.12), which has accelerated the transition toward innovation-driven, field-tested monitoring systems. Through Living Labs and lighthouse projects the Mission is actively developing and validating advanced sensing technologies (Internet of Things, proximal sensing), AI- and Machine Learning-based predictive models, real-time monitoring platforms, and participatory monitoring approaches (McPhee et al. 2021; Beaudoin et al. 2022).

In parallel, the establishment of the EUSO and its Soil Degradation Dashboard has created a fully integrated knowledge and monitoring platform, combining data, indicators, and policy-relevant outputs (Panagos et al. 2024b, 2024c). This represents a shift from data repositories to operational decision-support systems.

At the policy level, the SMRD introduces a legally binding framework for harmonised soil monitoring across the EU. It aims to define common soil health indicators, establish regular monitoring and reporting obligations, and link monitoring results to restoration targets and policy enforcement.

Technologically, this phase is characterised by the convergence of AI/ Machine Learning and big data analytics, high-resolution Remote Sensing, sensor networks and IoT, and Early Warning Systems (Golnaraghi 2012; UNEP 2012). Monitoring is thus transitioning toward predictive, near real-time, and risk-based systems, embedded within a broader monitoring–assessment–policy–restoration feedback loop.

A key evolution in this phase concerns the development of soil health indicators (Panagos et al. 2024c). Moving beyond traditional physical and chemical metrics, there is increasing emphasis on soil biodiversity and biological functioning (Pulleman et al. 2012), ecosystem service delivery (Borrelli et al. 2016), and threshold-based indicators (EEA 2023; Matson et al. 2024) linked to soil health status. The EUSO Soil Degradation Dashboard assessments on soil health are based on state-of-the-art indicators of soil degradation that are well-recognized and accepted throughout the soil community (Bünemann et al. 2018). Besides, the SMRD establishes 12 descriptors, encompassing indicators that address key soil degradation processes. These 12 descriptors are aligned with the eight indicators outlined in the Mission Soil implementation plan (Panagos et al. 2024c).

The transformation in soil monitoring is further reinforced by increasing environmental urgency (climate change, biodiversity loss, land degradation and desertification expansion, etc.), growing economic awareness of soil degradation costs, and expanding societal engagement, including citizen science and soil literacy initiatives.

However, challenges remain, particularly regarding indicator standardisation, cross-scale integration, and operational thresholds for action.

4.2.3.1. The EU Soil Observatory

Established in 2021, the EU Soil Observatory (EUSO) represents a major step forward in the transition from fragmented soil information systems to an integrated, policy-oriented soil monitoring framework. Its primary objective is to act as a central knowledge hub that supports the development, implementation, and evaluation of EU soil-related policies by providing harmonised data, indicators, and scientific evidence (**Figure 13**; Panagos et al. 2024b, 2024c).

EUSO builds upon and extends existing infrastructures, particularly the ESDAC (see § 3.3.2.2), by integrating diverse data streams into a coherent monitoring and assessment system. Its activities encompass the development of an operational EU-wide soil monitoring system, the consolidation of soil databases, the generation of policy-relevant indicators, and the facilitation of stakeholder engagement and citizen awareness (Panagos et al. 2024c). Through this integrative role, EUSO supports a wide range of policy domains, including climate action, agriculture, biodiversity conservation, and pollution control, reflecting the multifunctional role of soils in achieving sustainability targets (Montanarella and Panagos 2021b; Maréchal et al. 2022; Panagos et al. 2022a, b) (**Figure 13**).

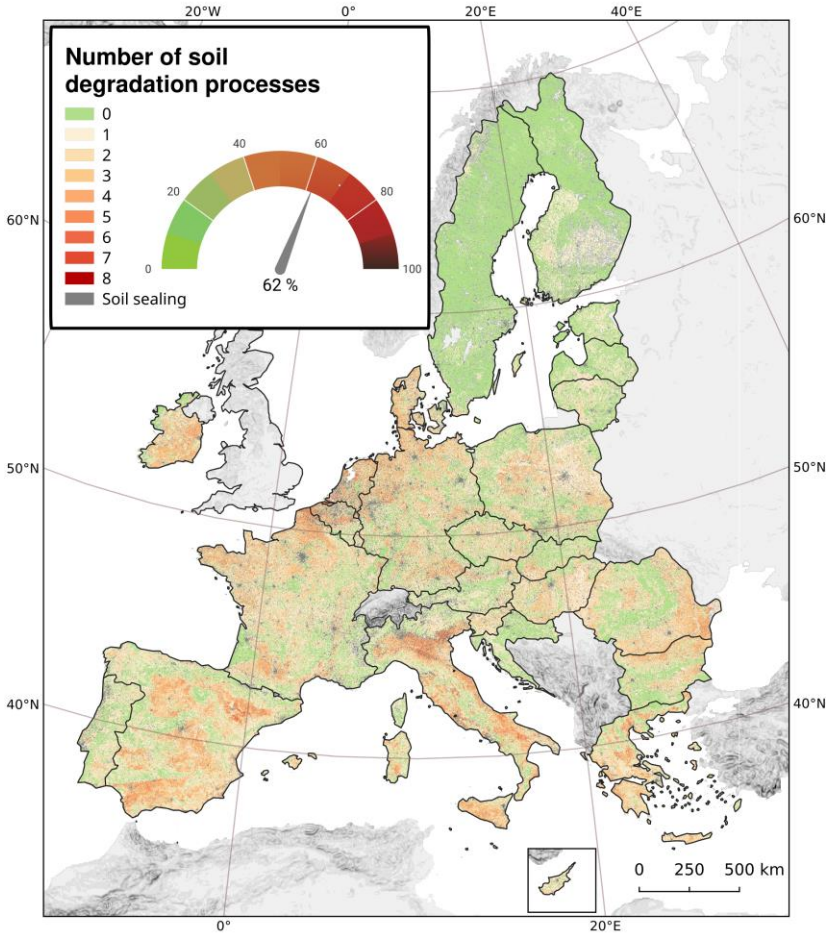
Figure 13. The main objectives of the EU Soil Observatory.



Source: Based on Panagos et al. (2024c).

A central component of EUSO is the EUSO Soil Degradation Dashboard, an innovative tool that synthesises multiple lines of evidence to assess the spatial distribution and intensity of soil degradation processes across the EU (**Figure 14**). The dashboard integrates up to 19 indicators related to key soil threats – such as erosion, contamination, soil sealing, biodiversity loss, and organic matter decline – allowing for a comprehensive evaluation of soil health status (Panagos et al. 2024c; Broothaerts et al. 2024). It provides not only static assessments but also insights into the co-occurrence and interaction of multiple degradation processes, thereby supporting more holistic and systems-based approaches to soil management. These outputs are made openly accessible to stakeholders through the Soil Degradation Dashboard platform.

Figure 14. The EUSO Soil Degradation Dashboard.



Source: Panagos et al. (2024c)

Beyond data integration, EUSO plays a key role in indicator development and policy alignment. It actively contributes to the definition and harmonisation of soil health indicators under both the SMRD and the EU Mission 'A Soil Deal for Europe', ensuring consistency between scientific monitoring frameworks and policy objectives (Panagos et al. 2024c). In this context, EUSO also supports the identification of knowledge gaps and promotes methodological innovation, including the use of spectroscopy, AI, and advanced modelling approaches for improved soil monitoring (Panagos et al. 2024c).

Another important dimension of EUSO is its role in fostering research, innovation, and collaboration. Through its Working Groups – covering thematic areas such as soil erosion, soil pollution, biodiversity, and data integration – it brings together experts from academia, policy, and industry to co-develop solutions to emerging soil challenges (Panagos et al. 2024b). These collaborative efforts contribute to the development of new datasets, modelling tools, and monitoring approaches, while also strengthening the link between scientific research and policy needs. In parallel, EUSO supports the Mission Soil by facilitating the uptake of research outputs into policy processes and by acting as an interface between research projects and EC services (Panagos et al. 2024c).

EUSO also plays a crucial role in stakeholder engagement and knowledge dissemination, promoting soil awareness among policymakers, scientists, and the public. Through initiatives such as soil atlases, citizen science activities, and stakeholder forums, it contributes to a broader societal

understanding of soil functions and the need for sustainable soil management (Panagos et al. 2024c). This participatory dimension is essential for ensuring that soil monitoring systems are not only scientifically robust but also socially relevant and policy actionable.

Looking ahead, EUSO is expected to further strengthen its role as the backbone of a dynamic, integrated, and policy-driven soil monitoring system in Europe. Planned developments include the continuous enhancement of the Soil Degradation Dashboard through the incorporation of new datasets (e.g. soil biodiversity, pollution, and emerging degradation processes), the integration of temporal dynamics to enable trend analysis, and the refinement of thresholds and uncertainty assessments across different pedo-climatic regions (Panagos et al. 2024c).

More broadly, EUSO is expected to play a pivotal role in supporting the transition from periodic soil assessments to continuous, multi-source monitoring systems, integrating traditional surveys (e.g. LUCAS), Earth Observation, in situ sensors, and modelling frameworks. Its expansion beyond Europe, including the development of soil health assessment frameworks in other regions (e.g. Africa), further highlights its potential as a global reference model for soil monitoring. Ultimately, by bridging data, science, and policy, EUSO contributes to a paradigm shift from monitoring soil conditions to understanding, managing, and restoring soil systems, thereby supporting the long-term goal of achieving healthy soils across the EU by 2050 (Panagos et al. 2024c).

4.2.3.2. Soil monitoring within the SMRD

As discussed in section 2.2.6, the SMRD (EU 2025/2360) – entered into force in December 2025 – represents the first dedicated piece of EU legislation to address soil as a distinct environmental compartment, placing it alongside the existing regulatory frameworks governing water, air, and the marine environment. The directive defines common soil descriptors and introduces classes to describe soil health, linked to non-binding EU-level target values and national trigger values — an architecture intended to help MS identify priorities and gradually implement measures leading to healthier soils. The overarching ambition is to bring all EU soils into a healthy condition by 2050, in line with the Zero Pollution and Biodiversity strategies.

At its core, the SMRD establishes a harmonized, multi-tiered monitoring system. Under the directive, MS are required to set up monitoring systems to assess the physical, chemical and biological condition of soils on their territory, based on a common EU methodology, and to regularly report to the Commission and the European Environment Agency on the state of soil health, land take and contaminated sites. The soil descriptors – covering properties such as SOC, soil structure, pH, nutrient status, contaminant loads, and biological indicators including microbial activity and soil fauna – are enumerated in Annexes I and II.

The criteria for healthy soil condition of the soil descriptors should be divided into non-binding sustainable target values (STVs) and operational trigger values (OTVs). The STVs should reflect the aspirational long-term objective of this Directive and do not create an obligation to act. Those non-binding STVs should reflect, based on the current scientific knowledge, the ideal situation whereby the capacity of soils to provide ecosystem services will not decrease and no significant harm will be caused to human health or the environment. However, bearing in mind the need for efficiency and the limited resources available, and in order to reflect local conditions, OTVs set by Member States are needed. Those OTVs should set in motion support to achieve soil health and soil resilience. For each aspect of soil degradation, one or several proportional and feasible OTVs should be set. Setting the trigger values at national level will ensure that local conditions and practices, soil use and current policies can be fully considered. Sampling follows a stratified design optimized for representativeness. The sampling scheme shall be a stratified random sampling optimized on the

best available information on the variability of soil descriptors, and the stratification shall be based on the soil units established in accordance to the Law. The law sets a target for the number of samples based on a coefficient of variation for the soil properties to be estimated, with the number and location of sampling points optimized to ensure a harmonized framework among MS (Panagos et al. 2025).

SMRD's principal strength lies in its commitment to harmonization. Prior to the proposal there was no agreed definition of what a healthy soil is, nor consensus on which indicators and thresholds should apply to each soil type, ecosystem, and climatic zone – resulting in an increase of incompatible national methodologies varying in field sampling protocols, analytical depths, laboratory procedures, and targeted indicators. By establishing common descriptors and a shared sampling methodology, the directive provides a basis for EU-wide comparability and the integration of national datasets with LUCAS. The framework also recognizes – and formally incorporates – soil biodiversity as a descriptor, an advance over most existing national programmes (Orgiazzi et al. 2016b). Politically, the tiered structure and the non-binding character of EU-level target values represent a pragmatic accommodation of MS autonomy, allowing countries with well-established monitoring systems to build on existing programmes rather than discard long-term datasets, thereby reducing administrative burden (Panagos et al. 2025).

Limitations

The first concerns the biological descriptors. Several ongoing Mission Soil-funded projects, such as AI4SH and BENCHMARKS, are pioneering the development of biological indicators – microbial diversity, soil fauna, and enzymatic activity – where current monitoring systems have major gaps with evidence from these projects expected to support future expansion of biodiversity monitoring within the directive's framework. The inclusion of biological parameters in the SMRD annexes is therefore partly aspirational: standardized, scalable methods for measuring soil biodiversity do not yet exist at the EU level, and their operational integration remains dependent on ongoing research.

A second and related challenge is spatial and typological heterogeneity. The EU encompasses an enormous diversity of soil types, land uses, and pedoclimatic conditions, and universal descriptor thresholds risk obscuring this variability. Soil policies have a strong local and territorial dimension due to widely differing ecosystems, soil composition, natural background concentrations, differences in land use, population density and climatic conditions, as well as different administrative structures – and this diversity must be considered through a fully applied multilevel governance approach to ensure clear, flexible and locally implementable soil descriptors and criteria. Forest soils illustrate the problem particularly well: specific indicators and thresholds applicable for the identification of degraded forest soils are needed, and the sampling and inventory design should consider the whole rooting zone of trees, the spatial heterogeneity of forest soils and the sampling of the forest floor – features not adequately captured by topsoil-focused, agricultural-centric protocols such as LUCAS (Wellbrock et al. 2024).

Third, the divergence between LUCAS and national soil monitoring systems poses a concrete comparability problem. Recent findings reveal significant differences between LUCAS Soil and national soil monitoring systems, with the latter generally covering a broader range of land covers, soil types and regions, with key soil properties including pH, SOC, nutrients and clay content showing marked differences when analyzed at national scale – meaning that LUCAS cannot serve as the sole EU soil monitoring system but must be complemented by national soil monitoring systems. Bridging these incompatible datasets will require the development of so-called 'transfer functions' – mathematical conversions between different sampling depths, laboratory protocols and measurement methods. The Mission Soil granted the project Soilharmony to develop validated

transfer functions which will reliably convert soil measurements to a common reference method and will facilitate a smooth and cost-effective transition to a harmonized soil health assessment across the EU. Existing knowledge does not yet cover the entire combination of laboratory and field methodologies in use across MS, meaning that a fully harmonized system remains technically incomplete at the time of the directive's adoption (Mason et al. 2025; Panagos et al. 2025; Yunta et al. 2026).

Finally, the flexibility built into the trigger-value system – while politically necessary – introduces the risk of fragmented implementation. Because operational thresholds are set at national level, the same soil descriptor may trigger remedial action at very different conditions in different MS, undermining cross-border comparability and potentially creating an uneven playing field in agricultural and land-use policy. To respect the autonomy of countries willing to implement more comprehensive monitoring systems, MS may choose among monitoring tiers with different soil descriptors and soil health criteria, but this flexibility, if not tightly coordinated, could ultimately compromise the pan-European coherence the SMRD is designed to achieve.

4.2.3.3. The role of Mission Soil in the progress of soil monitoring

The Horizon Europe Mission 'A Soil Deal for Europe' (Mission Soil) occupies a pivotal position in the transition to next-generation soil monitoring. Its funded projects are generating valuable data, knowledge, and tools for soil monitoring by combining traditional soil surveys with emerging data sources such as Remote Sensing, proximal sensing, and citizen science (Broothaerts et al. 2026). The Mission's three core operational pillars are directly relevant to closing the knowledge and implementation gaps identified in section 4.4.2:

— 100 Living Labs and Lighthouses: These real-life experimental sites, co-created with farmers, foresters, land managers, and citizens across diverse European biogeographical regions, are generating bottom-up, place-based evidence on soil health dynamics that cannot be captured by top-down satellite or modelling approaches alone (Panagos et al. 2024a, 2024c). By 2024, more than 45 Living Labs had commenced activities, while in 2025 another 20 LLs have started. Critically, they are designed to feed standardised soil health data into the EUSO, ensuring that field experimentation contributes to the EU-level monitoring evidence base.

— **Harmonised soil health indicator framework**: Mission Soil projects, including AI4SoilHealth and BENCHMARKS, are developing the harmonised top-down and bottom-up soil health indicator frameworks needed to operationalise the SMRD's monitoring requirements (Afshar et al. 2026). The AI4SoilHealth consultation with 30 policymakers across territorial levels identified persistent needs around integrating soil concerns into climate and energy policy frameworks and creating sustainable economic incentives – confirming that technical indicator development must be coupled with governance innovation.

— **Research and capacity building**: Funded projects such as ECHO (citizen science), TRAILS4SOIL (SMRD implementation tools) (https://trails4soil.eu/), EUROSION (erosion monitoring) (https://eurosion.eu/), and TERRASAFE (desertification in vulnerable regions) (https://terrasafe.eu/), NITROSCOPE (tracking nitrogen in EU soils) (https://nitroscope.eu/), MaRViC (https://www.project-marvic.eu/) and MRV4SOC (https://mrv4soc.eu/) (monitor, report and verify soil carbon and GHG balance), as well as MONALISA (desertification monitoring and restoration solutions) (https://monalisa4land.eu/), SALINOVA (soil salinity assessment and management) (https://cordis.europa.eu/project/id/101294352), and DeepHorizon (subsoil functions and soil health assessment) (https://deephorizon.eu/), are directly targeted at the knowledge and capacity gaps identified in soil monitoring. Their outputs – from monitoring protocols to governance models – will critically inform MS implementation of the SMRD by the 2030 deadline.

Translating these field-derived and modelled data streams into policy-actionable assessments requires robust conceptual frameworks for interpreting soil quality and health. Campbell et al. (2025) address this need through a proposed multi-scale framing of soil quality explicitly situated within the Mission Soil context, identifying three key challenges for continental-scale monitoring: the need to refine and update indicator datasets within the EUSO; the establishment of accepted thresholds or scoring methods for continuous indicators, flexible enough to account for land use, habitat type, and soil type; and the development of a composite soil index capturing both the extent and severity of quality, health, or degradation. Their framework underscores that clearly communicating the concept of soil quality is not merely a scientific exercise but an essential precondition for effective decision-making and resource allocation as the SMRD develops and monitoring occurs simultaneously across multiple scales.

Complementing this conceptual work, Alewell et al. (2026) present SHERPA (Soil Health Evaluation, Rating Protocol, and Assessment) – the first quantitative soil health assessment framework applied at European scale that explicitly accounts for soil genesis. By scoring all major soil degradation processes, averaging them, and subtracting from intrinsic soil health values, SHERPA produces spatially explicit, quantitative final scores that can directly support policy monitoring requirements. Critically, the framework demonstrates that meaningful pan-European soil health assessment is achievable with existing data, while also revealing where data gaps and inconsistencies most constrain the reliability of such assessments. SHERPA thus represents a significant methodological advance toward the kind of standardised, comparable, and policy-relevant soil health reporting that the SMRD will demand from MS.

Mission Soil is also catalysing wider pan-European and international soil research cooperation. Its Living Labs network, coordinated through the SOILL support structure, provides replicable models for scaling successful monitoring and management approaches across MS. The SoilWISE project (see section 3.3.3.2), designated as the Mission's open data platform, is developing the interoperability infrastructure for integrating Horizon Europe project outputs with EUSO and national monitoring systems – a critical missing link in current EU soil data architecture[75].

75 SoilWise aims to develop a centralized catalogue that compiles metadata from Mission Soil project outputs, along with other soil-related datasets and knowledge at the European level. The objective of this catalogue is to enhance the accessibility, discoverability, and usability of soil information across Europe, thereby supporting scientific research and advancing EU policy objectives on soil health. The catalogue is expected to play a crucial role in supporting the EUSO by facilitating the integration of currently fragmented soil datasets. In particular, it aims to

However, Mission Soil faces an inherent structural challenge: its funded projects operate on 4–5 year timeframes, while the soil knowledge and monitoring gaps they address require sustained, decades-long observation. Ensuring continuity of Living Lab data collection, open data archiving, and indicator monitoring beyond project funding cycles requires explicit long-term financial planning at both EU and MS levels (see section 4.4.5) – a challenge the Mission's current governance has not yet fully resolved.

4.2.3.4. The evolution of soil monitoring indicators at EU scale

An indicator is a proxy measure used to describe the status, evolution, or impact of a system – environmental, socioeconomic, or otherwise – across space and time (OECD 1993; EEA 2005; Faber et al. 2022). For instance, annual precipitation can indicate soil erosion risk, bedrock may signal susceptibility to desertification, and variables such as farmers' age, education level, or degree of organization can reflect a community's capacity to address soil degradation. Soil indicators – covering physical, chemical, and biological properties – constitute the primary tools through which soil assessment frameworks evaluate soil condition and functioning (Bünemann et al. 2018).

Importantly, indicators point to conditions of likelihood rather than certainty. Shallow soil, for example, suggests vulnerability to erosion but does not determine it in isolation, as other factors such as rainfall and slope must also be considered. Their main advantage lies in simplifying complex systems, enabling the interpretation of ecosystem status without requiring the processing of large datasets, while maintaining an acceptable level of accuracy. According to the Organization for Economic Co-operation and Development (OECD) (2004), effective indicators should be specific, measurable, achievable, relevant, and time-bound, while also relying on accessible, high-quality, and interpretable data. They are typically framed by benchmarks, which establish reference conditions for comparison, and thresholds, which define critical transition points between system states, expressed either numerically (e.g. vegetation cover percentages) or qualitatively (e.g. low, moderate, high).

In environmental systems characterized by strong spatial and temporal variability, such as soils, single indicators are often insufficient. Composite indices are therefore employed, to combine multiple variables and better capture system dynamics, particularly since the suitability – or quality (Harvey and Green 1993) – of a given soil attribute for one function does not necessarily imply its adequacy for another.

Indicators also play a central role in evaluating policy performance, supporting the assessment of progress toward defined objectives while communicating complex information in an accessible way (Ritz et al. 2009; Reynolds et al. 2013; Orgiazzi et al. 2018). Their careful selection is essential for strengthening policy guidance and advancing sustainable soil management (Bünemann et al. 2018). As Campbell et al. (2025) argue, their interpretation is shaped by the quality framework within

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make data and knowledge generated by Mission Soil projects – and other relevant sources – easily discoverable and accessible to a wide range of users, including researchers, policymakers, and practitioners. A key objective is to ensure that the catalogue evolves into a long-term resource rather than remaining a short-lived project output. To this end, the catalogue will be hosted and maintained by EUSO after the completion of the SoilWise project. Furthermore, EUSO plays a central coordinating role by aligning efforts among the Directorate-General for Agriculture and Rural Development (DG AGRI), the European Research Executive Agency, and the SoilWise consortium. This coordination is essential to ensure the effective implementation of the catalogue, given its strategic importance for the future development of both EUSO and the SMRD. Under EUSO guidance, a set of key requirements has been defined to ensure the catalogue's success.

which they are deployed – whether oriented towards 'fitness for purpose', 'free from degradation'[76], 'external benchmarking' or 'value assessment' – which in turn determines both indicator choice and the use of results. However, identifying appropriate soil indicators at the pan-European scale remains challenging, due to variability in climate, topography, geology, and soil types, leading to differing drivers and soil processes across pedo-climatic zones (Stone et al. 2016; Campbell et al. 2025).

The systematic monitoring of soil health at EU scale has undergone substantial evolution over the past decades, shifting from a limited suite of largely chemical and physical descriptors to an increasingly comprehensive, multi-functional framework. Prior to the EUSO establishment in 2021 and the expansion of LUCAS, only a restricted number of indicators for soil degradation processes were operationally available at continental scale. The progressive development of the EUSO Soil Degradation Dashboard – initially encompassing 15 indicators and subsequently expanded to 19, with further additions planned[77] – represents a significant milestone in this trajectory, providing for the first time a spatially explicit, convergence-of-evidence assessment of where and how EU soils are degrading (Panagos et al. 2024c). The thematic, temporal and spatial coverage of soil monitoring has improved markedly: more soil degradation processes are now tracked, seasonal and multi-annual trends are captured through repeated campaigns, and monitoring now encompasses all major land uses – including urban, grassland and woodland systems – rather than focusing exclusively on agricultural soils as was historically the case.

Living Labs established under Mission Soil, together with existing monitoring systems, play a key role in generating bottom-up best practices for sustainable soil management. They also provide opportunities to implement 'fitness-for-purpose' approaches – such as scorecards or external benchmarking – to enhance soil health, potentially incorporating additional or context-specific indicators tailored to local conditions (Stone et al. 2016). The SMRD's 12 descriptors are closely aligned with the eight indicator groups of the Mission Soil implementation plan, providing institutional coherence between the research and regulatory agendas (Panagos et al. 2024c). Figure 2.3 illustrates the set of Mission Soil indicators (right panel) and maps their contribution to achieving each of the Mission Soil specific objectives (left panel).

Nevertheless, important bottlenecks persist (see section 4.4.1). The binary degradation approach does not capture the degree or severity of soil health decline, nor does it formally recognize the diverse functional capacities of soils across pedoclimatic zones – a limitation that Campbell et al. (2025) identify as particularly acute at local management scales, where 'fitness for purpose' and 'external benchmarking' approaches would be more appropriate and informative. The development of accepted, locally calibrated indicator thresholds remains an unresolved challenge: thresholds for properties such as SOC are highly sensitive to soil type, climatic context and land cover, making

76 The current EU approach, as embodied in both the EUSO Soil Degradation Dashboard and the SMRD, is predominantly anchored in a 'free from degradation' paradigm that assesses soil quality as a binary condition relative to defined degradation thresholds (Panagos et al. 2024c; Campbell et al. 2025).

77 Future developments of the dashboard envisage regular updates to improve the assessment of soil degradation processes (Prăvălie et al. 2021), including the incorporation of new indicators targeting emerging challenges such as diffuse pollution and biodiversity. Furthermore, existing indicators will be further refined to better reflect variability across pedo-climatic conditions, alongside increased collaboration with Mission Soil–funded projects to support more comprehensive and robust monitoring (Panagos et al. 2024a, 2024c).

universal EU-wide values a poor substitute for context-specific benchmarks (Feeney et al. 2023; Drexler et al. 2022).

Biological indicators represent perhaps the most critical gap: although the SMRD's annexes include descriptors for soil biodiversity, and the EUSO Soil Degradation Dashboard incorporates a proxy for potential threats to biological functions based on Orgiazzi et al. (2016a), standardized and operationally scalable methods for measuring microbial diversity, soil fauna abundance, and enzymatic activity are still under development across Mission Soil projects. The EUSO itself acknowledges that maps of soil microorganism richness and diversity, along with indicators for beneficial organisms such as nitrogen-fixing bacteria and symbiotic fungi, remain forthcoming (Panagos et al. 2024c).

Finally, an important structural challenge is data fragmentation: national soil monitoring systems continue to use incompatible methodologies and sampling depths, and the development of pedo-transfer functions to harmonize legacy datasets with LUCAS protocols – although underway through the LUCAS 2022 double-sampling exercise – is not yet complete (Panagos et al. 2024c).

4.2.3.5. Citizen science

Citizen science was initially conceptualized by Irwin (1995) as science conducted 'by' and 'for' the public (Strasser et al. 2019). The central idea is that scientific inquiry should address societal concerns and incorporate citizens' local knowledge and lived experience, thereby complementing academic expertise (Wadoux and McBratney 2023). A widely used definition was later proposed by Bonney et al. (2009), who described citizen science as '*non-scientists contributing to scientific data and as a tool for public education to science*.' Engagement of citizen scientists can strengthen connections between people and their natural environment and foster a sense of stewardship toward local ecosystems (Larson et al. 2020).

In the context of soil monitoring specifically, citizen science offers considerable added value by enabling spatially dense, repeated observations that would be logistically and financially prohibitive through conventional survey approaches alone (Pocock et al. 2021). Several initiatives have demonstrated the potential of citizen-collected soil data across a range of indicators. The Worm Watch Lab, hosted on the Zooniverse platform, engages citizens in classifying earthworm activity from field footage, providing data directly relevant to soil biological health indicators (Robinson et al. 2018). The GLOBE Observer programme, coordinated by NASA, deploys standardised soil moisture and land cover protocols across schools and citizen observer networks worldwide, with outputs used to validate satellite-derived soil products (Kohl et al. 2021; Nelson et al. 2024). The work of Fritz et al. (2017) provides a list of examples of crowdsourcing and citizen science initiatives relevant to Earth Observation. On-line open-access platforms such as OpenLandMap (Hengl et al. 2026) and iNaturalist have further enabled georeferenced, opportunistic soil observations – including texture, colour, and biological diversity – that can complement systematic survey frameworks when appropriately quality-controlled. In ecology, citizen science has proven particularly valuable for biodiversity monitoring, as it enables the collection of large datasets across extensive spatial scales (Crall et al. 2010; Pocock et al. 2018).

Despite these promising examples, the integration of citizen science data into formal continental-scale soil monitoring frameworks remains challenging. Key barriers include inconsistencies in measurement protocols across national contexts, variable observer training and equipment, and the absence of standardised data formats compatible with institutional repositories such as the LUCAS or the Soil Degradation Dashboard. Data coverage is inherently uneven, with higher participation in densely populated or well-connected regions, introducing spatial biases that can compromise

representativeness at the continental scale (Haklay 2013). Furthermore, citizen-generated soil data often lack the metadata richness required under FAIR data principles, limiting their reusability and interoperability with existing monitoring datasets (Wilkinson et al. 2016). Addressing these limitations requires investment in harmonised protocols, robust quality assurance pipelines, and policy frameworks that formally recognise citizen science data as a legitimate input to soil monitoring – a recognition that is currently absent in most European regulatory contexts (Eitzel et al. 2017).

A comparative study of the methodology[78] used by citizen scientists against conventional laboratory analysis, applied by the EUSO and partners from the Free University of Bolzano, is being conducted on a subset of soil samples collected in Italy within the framework of the Mission Soil ECHO[79] project. The study aims to: i) evaluate the consistency between citizen science-derived measurements and conventional laboratory analyses, while accounting for potential biases and uncertainties in citizen-generated data through advanced statistical approaches such as mixed-effects and hierarchical modelling (Bird et al. 2014; Royle and Dorazio 2008), ii) assess the feasibility of integrating ECHO-derived data into the Soil Degradation Dashboard, including considerations of data protection (GDPR) and the development of meaningful aggregated indicators, and iii) examine the comparability of ECHO datasets with those obtained from established monitoring frameworks such as LUCAS.

The TeaComposition Initiative is a standardized, low-cost global approach to measuring litter decomposition using the Tea Bag Index, where citizen scientists bury commercially available Lipton tea bags (green and rooibos) for approximately three months and assess weight loss as a proxy for soil carbon cycling and decomposition dynamics (Keuskamp et al. 2013). The initiative mobilizes a wide network of participants – including researchers, schools, and institutions – while leveraging existing global infrastructures such as long-term ecological research networks, international organizations, and protected area systems (Ivashchenko et al. 2024). Its strength lies in its simplicity and scalability, relying on widely accessible materials and a harmonized protocol that enables cross-site comparison of decomposition rates. However, its implementation is not without constraints, including dependencies on supply chains (e.g. changes in tea bag materials), and a heavy reliance on voluntary researcher time for data processing, which can divert effort from core scientific outputs. Despite its elegant design and global applicability, the Initiative exemplifies many of the systemic barriers that hinder the broader upscaling of citizen science approaches (**Table 7**).

A notable regional example of citizen science is the Flemish *CurieuzeNeuzen in de Tuin* project (https://watchitgrow.be/en/new-measurement-campaign-curieuzeneuzen-de-tuin-2022), which mobilised thousands of citizens to collect high-resolution data on soil moisture and temperature using smart sensors installed in gardens, public green spaces, and agricultural areas. The initiative aimed to improve understanding of how landscapes respond to heat and drought stress under changing climatic conditions, while demonstrating the value of large-scale citizen-generated datasets for environmental monitoring. The collected observations were integrated with scientific

78 Digital image analysis, colorimetric approaches, and visual assessment.

79 The ECHO (Engaging Citizens in soil science: the road to Healthier sOils) project (2023-2027), funded under Horizon Europe, is designed to actively involve citizens in soil monitoring by enabling them to collect data on soil properties across diverse land uses, soil types, and biogeographical regions (https://mission-soil-platform.ec.europa.eu/index.php/
project-hub/echo). Through structured protocols and tailored citizen science initiatives, participants contribute to large-scale datasets that complement existing monitoring systems such as LUCAS and EUSO.

analyses, remote sensing information, and digital platforms, illustrating how citizen science can complement conventional monitoring networks and strengthen public engagement in soil and climate resilience.

Table 7. Systemic barriers limiting the scalability and long-term sustainability of citizen science initiatives, highlighting financial, institutional, technical, and social constraints, as identified by the TeaComposition Initiative.

Barrier	Description
Funding trap	Reliance on short-term grant cycles with limited support for long-term infrastructure
Impact gap	Difficulty demonstrating real-world outcomes beyond participation metrics
Policy rejection	Lack of formally certified data acceptable for policy and governance use
False openness	Data may be nominally open but practically inaccessible or unusable
Not designed to scale	Scaling requires additional IT, administrative, or logistical resources
Hidden administrative burden	Significant time spent on data validation, coordination, and maintenance
Resource intensity	New participants require support that core teams cannot sustainably provide
Local DNA	Success depends on context-specific factors that may not transfer elsewhere
Long-term involvement	Sustaining engagement is difficult due to volunteer fatigue
Co-ordination / management of data	Lack of a data structure (such as ESDAC) to host citizen science data

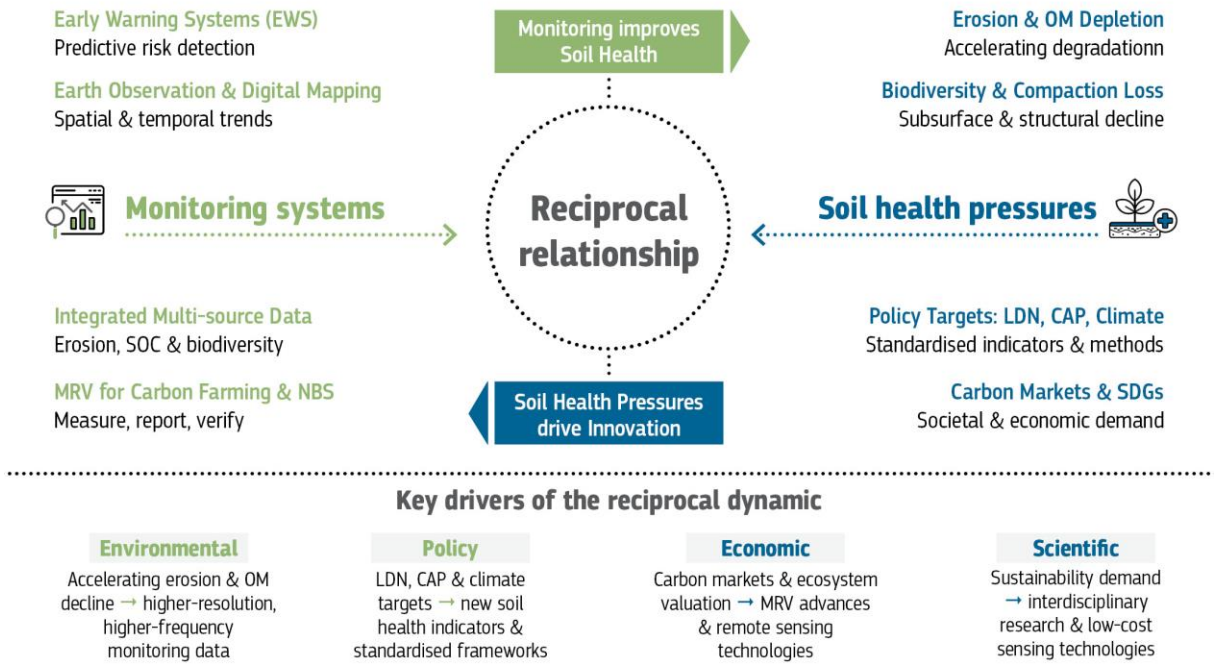
Source: Based on the TeaComposition Initiative.

4.3. Impacts of monitoring evolution on soil health: a dynamic and reciprocal relationship

The evolution of soil monitoring systems in the EU has had a profound influence on better understanding soil conditions, introducing more effective policies and practices, and ultimately improving soil health. This influence, however, has not been unidirectional. Rather, it reflects a dynamic and reciprocal relationship, in which advances in monitoring have shaped soil health outcomes, while emerging soil degradation challenges and SDGs, and the increased data demand, have simultaneously driven the development of more sophisticated monitoring tools.

Figure 15 conceptualizes this interaction by showing how soil health pressures – such as erosion, organic matter depletion, biodiversity loss, and compaction – stimulate innovation in monitoring systems, including Earth Observation, Digital Soil Mapping, Early Warning Systems, and integrated multi-source data platforms. In turn, these monitoring systems provide the evidence base needed for policy implementation, measure-report-verify frameworks, land management decisions, and the evaluation of soil restoration and climate-related targets. The figure also highlights that this reciprocal dynamic is reinforced by environmental, policy, economic, and scientific drivers, which together shape the evolution of soil monitoring in Europe.

Figure 15. The reciprocal relationship between monitoring evolution and soil health improvement.



Source: JRC analysis.

Positive impacts: from visibility to informed action

One of the most significant contributions of improved monitoring systems has been the enhanced visibility of soil degradation processes. Early monitoring efforts, limited in spatial and temporal resolution, often failed to detect gradual or diffuse forms of degradation such as SOC decline, compaction, or biodiversity loss. The transition toward integrated, multi-source monitoring systems has enabled i) systematic identification of soil degradation hotspots for e.g. soil erosion (Efthimiou et al. 2020; Alexiou et al. 2023), organic matter depletion (Lin et al. 2020b; Liu et al. 2025), etc., ii) quantification of trends over time (Carvalho-Santos et al. 2018; Gallo et al. 2018), supporting the assessment of policy effectiveness, and iii) evidence-based policymaking (Panagos et al. 2024c). As a result, monitoring has contributed to the mainstreaming of soil protection within broader environmental and agricultural policy frameworks. Furthermore, the integration of Earth Observation, digital soil mapping, and modelling has enhanced the capacity to anticipate risks rather than merely document impacts. Indicative examples include the work of Reyes et al. (2024), who developed a predictive monitoring framework integrating UAV multispectral imagery and field data to model and map the spatial variability of SOC, and the study by Stevens et al. (2013), which applies a spectroscopic modelling approach to predict SOC at the continental (EU) scale, supporting large-scale soil monitoring. This shift toward predictive monitoring supports Early Warning Systems, targeted interventions, and improved land management practices. In this sense, monitoring has evolved from a descriptive tool into a proactive instrument for soil health preservation and restoration.

Limitations and negative effects: gaps, biases, and over-reliance on proxies

Despite these advances, the evolution of monitoring systems has also introduced certain limitations that may constrain their effectiveness in improving soil health. A key challenge lies in the indirect nature of many monitoring indicators. Soil health is a complex, multidimensional concept,

encompassing physical, chemical, and biological properties. However, large-scale monitoring systems often rely on proxies – such as indicators (Bünemann et al. 2018) or models (Panagos et al. 2015a) – that may not fully capture underlying soil conditions. This has led to i) potential misrepresentation of soil health status, particularly for subsurface or biological processes, ii) uneven coverage of soil functions, with stronger emphasis on erosion and carbon than on biodiversity or soil structure, iii) risk of policy bias, where what is measurable becomes prioritised over what is ecologically important. In addition, the increasing reliance on model-based approaches introduces uncertainties related to data quality and resolution, model assumptions, integration of heterogeneous datasets. These limitations highlight that monitoring, while essential, does not automatically translate into improved soil health without careful interpretation and complementary field validation.

The role of monitoring in shaping soil management practices

Improved monitoring systems have influenced not only policy but also on-the-ground land management decisions. The availability of spatially explicit and increasingly accessible data has enabled more precise targeting of agri-environmental measures, development of site-specific management practices, and increased accountability at both local (Zhang et al. 2022; Belton et al. 2025; Ford and Wätzold 2026) and continental level (ECA 2020[80]), through monitoring and reporting requirements. At the same time, the expansion of monitoring has contributed to the emergence of new management paradigms, such as carbon farming (Sharma et al. 2021; Strauss et al. 2024), NBS (Chrysoulakis et al. 2021; Giuliani et al. 2024; Moolchandani 2026), and soil health-oriented land stewardship (Deshmukh et al. 2025; Sadiq et al. 2025). These approaches rely heavily on the ability to measure, report, and verify soil conditions, further reinforcing the central role of monitoring in shaping soil management.

A reciprocal relationship: soil health as a driver of monitoring innovation

While monitoring has influenced soil health outcomes, the relationship is equally driven in the opposite direction. The growing recognition of soil degradation as a critical environmental and socio-economic issue has acted as a powerful catalyst for innovation in monitoring systems. Several factors illustrate this reciprocal dynamic (**Figure 15** and **Table 8**).

Table 8. Drivers of the reciprocal relationship between soil monitoring and soil health.

Driver category	Key drivers	Implications for monitoring systems
Environmental pressures	Accelerating soil degradation processes (e.g. erosion, desertification, organic matter decline)	Demand for higher-resolution data, increased observation frequency, and improved detection of early-stage degradation
Policy targets and reporting requirements	Climate mitigation, biodiversity protection, and LDN objectives	Development of new soil health indicators, standardized methodologies, and integrated monitoring frameworks

80 At the continental level, the adoption of modern Remote Sensing technologies (e.g. Copernicus Sentinel data) has enabled continuous and automated monitoring of agricultural land within the context of the CAP, supporting full spatial coverage, reduced reliance on field inspections, and a shift toward more proactive and preventive compliance systems (ECA 2020).

Driver category	Key drivers	Implications for monitoring systems
Economic and market mechanisms	Emergence of carbon markets and ecosystem service valuation	Advances in soil carbon monitoring, Measure, Report, Verify systems, and digital/RS technologies
Societal and scientific demand	Increased awareness of soil importance and sustainability challenges	Growth of interdisciplinary research, citizen science initiatives, and innovation in low-cost sensing technologies

Source: JRC analysis.

4.4. Outlook and perspectives

Soil monitoring in Europe is expected to transition from periodic assessment exercises towards continuous, adaptive, and risk-based systems capable of informing timely intervention and restoration. Realising this transition is, however, far from straightforward. It demands not only technical advances but also a fundamental rethinking of knowledge architectures, governance frameworks, and investment commitments. Building on the trajectory described in previous paragraphs, this section synthesises the key requirements for advancing soil monitoring and governance. It examines the critical knowledge gaps that continue to constrain effective assessment, the pathways for addressing these gaps, the conditions needed to integrate emerging data sources with traditional soil observation networks, the role of Mission Soil in catalysing this transition, and targeted recommendations for policymakers. It closes with a call for sustained investment in soil monitoring and mapping as a long-term European public good.

4.4.1. Critical knowledge gaps

Despite considerable progress in European soil science and monitoring infrastructure over the past decade, several foundational knowledge gaps remain that directly constrain the effectiveness of both current and future monitoring systems (Table 4.3).

Table 9. Knowledge gaps in European soil monitoring.

Field	Key gap
Soil biodiversity	Absence of harmonized, long-term soil biodiversity monitoring protocols and reference databases across EU biogeographical regions, land uses, and taxonomic groups
SOC and subsoil carbon	Insufficient long-term, depth-resolved, and spectrally harmonized SOC monitoring data to validate temporal change detection at the EU scale; inadequate uncertainty quantification frameworks for EO-derived SOC trend estimates
Indicator standardization and cross-system interoperability	No agreed, legally operational set of common soil health descriptors, thresholds, and measurement protocols applicable across EU MS, land use types, and soil threats
Soil contamination, sealing, and emerging threats	Systematic gap in contamination monitoring (pesticides, microplastics, emerging pollutants) and near-complete absence of frameworks for detecting and attributing compound, multi-threat soil degradation dynamics

Source: JRC analysis.

Soil biodiversity

Soil biodiversity represents perhaps the most critically under-monitored dimension of soil health in Europe. It is estimated that around half of all biodiversity on Earth resides in soils, yet long-term quantitative data on soil organism communities are largely absent at the pan-European scale (https://www.biodiversa.eu/2024/02/01/pilot-on-soil-biodiversity-monitoring-first-year-report/). The Biodiversa+ soil biodiversity monitoring pilot (2023–2024), involving 13 countries including forest sites across diverse biogeographical regions, confirmed that consistent, comparable data on soil invertebrate and microbial communities (e.g. microbial functionality and resilience) are almost entirely lacking, impeding any meaningful baseline assessment of trends or thresholds. High-Throughput Sequencing (HTS[81]) and eDNA[82] techniques have transformed species identification, but have not yet been integrated into operational, standardised monitoring protocols at the EU level. A comprehensive review of 507 references on soil biodiversity policy coverage found that only eight EU MS explicitly address threats to soil biodiversity in regulatory instruments, while six countries make no provision whatsoever (Köninger et al. 2022). The studies of Orgiazzi et al. (2016b) and Minasny et al. (2017) highlight that soil functions cannot yet be reliably inferred across scales due to data fragmentation and methodological inconsistencies.

SOC and subsoil carbon: depth, dynamics, and temporal uncertainty

While surface SOC receives extensive monitoring attention, subsurface carbon stocks – which can account for more than 50% of total soil carbon – remain poorly characterised across European landscapes. Moreover, even where surface SOC is monitored via Remote Sensing and modelling, uncertainty over temporal trends remains a fundamental problem. A 36-year spatiotemporal analysis using Landsat and Sentinel-2 data on European croplands demonstrated that while static SOC prediction accuracy was reasonable (R^2 = 0.61), the direct validation of derived SOC trends showed substantially greater uncertainty (R^2 = 0.16), highlighting that monitoring systems calibrated for spatial mapping cannot reliably track slow temporal dynamics without dense, long-term ground-truth networks (Broeg et al. 2024). Ding et al. (2025) further document that despite rapid expansion in ML and deep learning approaches to SOC estimation, Bayesian and stochastic uncertainty quantification methods remain computationally expensive and perform poorly under conditions outside their training domains – a critical vulnerability for monitoring under novel climate extremes. The absence of harmonised reference soil spectral libraries further limits the transferability of proximal and remote sensing SOC models across MS.

Indicator standardisation and cross-system interoperability

One of the most pervasive structural gaps in European soil monitoring is the fragmentation of indicator definitions, sampling protocols, laboratory methods, and reporting formats across MS and monitoring networks.

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81 Refers to advanced DNA sequencing technologies that enable the rapid and simultaneous analysis of millions of genetic fragments from soil samples, allowing comprehensive characterization of soil biodiversity, including microorganisms that cannot be detected using traditional methods. Within Mission Soil, HTS represents an emerging tool for integrating soil biodiversity and biological functioning indicators into soil health assessments, complementing physical and chemical measurements required for comprehensive soil monitoring.

82 Refers to genetic material released by organisms into their environment (e.g. soil, water, air) through cells, tissues, or metabolic waste; its analysis allows the detection and identification of species without direct observation or sampling of the organisms themselves, making it a powerful tool for biodiversity monitoring.

Soil contamination, sealing, and emerging threats

Substantial knowledge gaps persist around contamination – particularly from pesticides, microplastics, per- and polyfluoroalkyl substances (PFAS), organic pollutants, and pharmaceuticals – and around soil sealing in rapidly urbanising regions. Pump et al. (2024) document that data on soil contamination are highly uneven across the EU, with systematic national monitoring of pesticide residues in soils absent in most MS. The SMRD includes provisions on contaminated site identification and management, representing a significant step, but the absence of baseline contamination maps across land uses and soil types limits the effectiveness of any risk-based monitoring approach. More broadly, multi-threat interactions – where, for example, compaction, salinisation, and biodiversity loss co-occur and amplify each other – remain poorly characterised in observational datasets, which tend to track single stressors in isolation.

4.4.2. Pathways to filling the knowledge gaps

Harmonised, long-term field monitoring infrastructure

No amount of Remote Sensing or modelling sophistication can substitute for high-quality, long-term, depth-resolved field observations collected using harmonised protocols. Priority investments are needed to: extend existing national soil monitoring networks (SMNs) to sub-national resolution and to land use types currently underrepresented (urban soils, forests, wetlands); implement standardised multi-depth sampling at a meaningful subset of LUCAS sites and national network nodes; and create open, FAIR-compliant data infrastructures enabling cross-national data fusion. The EUSO provides an important institutional backbone for such investments but requires further redevelopment.

Integration of earth observation, proximal sensing, and digital modelling

The full potential of hybrid monitoring frameworks – combining (continuous) Copernicus satellite coverage, (low-cost) ground sensor networks, and targeted field validation – has not yet been operationalised at scale. Key technical steps include: developing harmonised soil spectral libraries for SOC and key nutrient calibration across EU pedoclimatic zones; establishing protocols for EO-derived product validation against field measurements, including explicit uncertainty quantification (Broeg et al. 2024); integrating proximal sensor networks (including IoT-based soil moisture, temperature, and electrical conductivity sensors) with satellite time series for continuous, near-real-time soil condition tracking; and embedding advanced AI and process-based hybrid models that can constrain SOC trend estimates using biogeochemical process knowledge, reducing reliance on statistical correlations that may break down under novel climate conditions (Ding et al. 2025).

PREPSOIL has documented key bottlenecks to the upscaling of Earth Observation for soil monitoring, including limited capacity for end-user training, lack of semantic and syntactic interoperability between Earth Observation data products and national soil databases, and insufficient standardisation of soil health indicator operationalisation from Remote Sensing (https://prepsoil.eu/). Addressing these requires dedicated capacity-building investments alongside technical development.

Citizen science and participatory data collection

Citizen science represents an underutilised but rapidly maturing approach to filling geographic and taxonomic gaps in soil monitoring. The Horizon Europe ECHO project is developing tailor-made citizen science initiatives across EU MS, with the objective of generating complementary soil health data and building ECHOREPO – a long-term open-access citizen science data repository

(https://echorepo.quanta-labs.com/explore). PREPSOIL has further assessed the feasibility and conditions for citizen science engagement in soil monitoring, highlighting that data quality, representativeness, and FAIR data standards are achievable with appropriate protocols and digital tools (Charvat et al. 2024). Thorsøe et al. (2023) identify peer-to-peer communication and farmer-to-farmer knowledge exchange as among the most effective mechanisms for translating soil monitoring findings into management change – underscoring that citizen science in soil monitoring must be designed as a two-way knowledge exchange, not merely a data extraction exercise.

Governance, knowledge brokerage, and translation

Technical data collection alone does not produce improved soil management. A persistent and widely documented gap lies in the translation of multi-source soil monitoring signals into actionable guidance for land managers, environmental authorities, insurers, and risk managers. Thorsøe et al. (2023) identify seven recommendations from European soil knowledge stakeholders – including strengthening knowledge brokers, targeting advice to specific user groups, and providing incentives linked to monitoring outcomes – that go beyond indicator development to address the institutional conditions for knowledge uptake. The ECA Special Report on EU efforts for sustainable soil management (ECA 2023) concluded that CAP tools were not used sufficiently and that MS often set unambitious national requirements, partly due to insufficient connection between monitoring findings and policy enforcement mechanisms. Governance coordination across administrative levels – from EU to MS to regional and farm level – is therefore as critical as technical monitoring capacity.

Soil Health Indices: Opportunities and Limitations

Given the multidimensional nature of soil health, the integration of individual indicators into a composite **Soil Health Index** has received increasing attention. Composite indices offer several advantages over the interpretation of individual indicators in isolation. By combining physical, chemical, and biological measurements into a single metric, they facilitate communication with policymakers, land managers, and other stakeholders, support comparisons across sites and regions, and provide a practical tool for monitoring trends and evaluating management interventions.

However, there is no universally applicable Soil Health Index. The selection of indicators, aggregation methods, weighting schemes, and reference values depends strongly on the purpose of the assessment, the spatial scale considered, and the needs of the end users. Indicators suitable for farm-level management decisions may differ substantially from those required for national reporting or scientific investigations of ecosystem functioning. Consequently, it is more appropriate to refer to a soil health index framework rather than a single Soil Health Index, as different contexts require different combinations of indicators and methodologies.

At the same time, composite indices present several limitations. Aggregating multiple indicators into a single score may mask important information about individual soil functions and trade-offs between them. The weighting assigned to different indicators can introduce subjectivity and may influence the final outcome significantly. Furthermore, index performance is often sensitive to the selection of reference values, normalization procedures, and aggregation methods, making comparisons across studies difficult. Another challenge is that some key soil properties, particularly biological indicators, remain costly or difficult to measure consistently across large spatial scales. As a result, composite indices should be viewed as decision-support tools that complement, rather than replace, the interpretation of individual soil indicators.

Future developments are likely to focus on flexible and modular soil health index frameworks that can accommodate different policy objectives, environmental conditions, and user requirements while maintaining sufficient harmonization to enable comparisons across regions and monitoring systems.

4.4.3. Full integration of new data sources and traditional soil monitoring

The question of how to achieve genuine integration – rather than mere co-existence – of Earth Observation, sensor networks, citizen science, and traditional soil surveys deserves particular attention, as it remains unresolved in both technical and institutional terms.

From a technical standpoint, integration requires:

- Shared data standards enabling semantic interoperability between Earth Observation-derived products and field-measured soil properties.
- Common spatial and temporal reference frameworks enabling data fusion across heterogeneous observation systems.
- Explicit uncertainty propagation from raw observations through to final soil health indicators.
- Model validation chains that ground-truth Earth Observation and modelled outputs against representative, independently collected field data.

Advances in EU optical Earth Observation for policy support (Berger et al. 2025) demonstrate that Earth Observation variables can increasingly be linked to specific soil-related policy requirements under the SMRD, CAP, LULUCF, and CRCF frameworks – but that the technology readiness levels of many soil indicators remain low, particularly for subsurface properties and biological attributes.

From an institutional standpoint, integration requires: national soil monitoring authorities to adopt interoperable data formats compatible with ESDAC ingestion; harmonised laboratory reference standards (e.g. ISO-certified protocols for SOC, pH, and texture) to enable cross-national comparison of field measurements; and data governance frameworks that balance open access with the legitimate data sovereignty interests of MS and private data holders (e.g. precision agriculture data from farms). The EU Soil Health Portal, envisaged as an evolution of ESDAC 2.0, is designed as the central integration platform, incorporating national data flows, Mission Soil project outputs, and satellite products from Copernicus under a unified soil information architecture (Panagos et al. 2024c). Achieving this vision requires sustained multi-year co-investment and a clear legal mandate – which the SMRD, once fully transposed, is intended to provide.

4.4.4. Policy recommendations

On the basis of the analysis above, and informed by the scientific literature reviewed throughout this chapter, the following targeted recommendations are offered to EU and MS policymakers:

Anchor monitoring within enforceable legal obligations

The SMRD must be implemented with ambitious rather than minimally compliant national monitoring frameworks. To maximise the effectiveness of the SMRD, MS should strengthen national monitoring capacities, ensure continuity of soil observations, and establish mechanisms that support the long-term collection, harmonisation, and use of soil data. Looking ahead, greater integration between soil monitoring systems and policy instruments such as the CAP could create incentives for improved data quality and soil stewardship. Linking reliable soil information with

result-based approaches and restoration objectives could strengthen accountability while rewarding land managers for practices that maintain and improve soil health.

Mandate harmonised indicators and interoperable data architectures

All EU-funded soil monitoring data should be required to comply with FAIR data principles and ESDAC ingestion standards as conditions of grant agreements.

Building on the identified gaps in soil monitoring and the need for more harmonized, operational frameworks, recent policy-oriented work within the EJP SOIL programme provides practical guidance on how to integrate biological indicators into soil health assessments. In particular, Mocali et al. (2025) propose a structured yet flexible approach that balances scientific robustness with implementation feasibility across EU MS. Their recommendations emphasize tiered indicator systems, integration across soil functions, and adaptive monitoring strategies that reflect current data limitations while supporting future standardization (**Table 10**).

Table 10. Key recommendations for integrating soil biological indicators into soil health monitoring frameworks.

Recommendation	Description
Tiered approach	Establish a two-level system: Tier I includes a core set of harmonized indicators applicable in all contexts; Tier II includes additional, context-specific indicators selected by MS when Tier I results indicate potential soil health issues
Apply tier I indicators	Use all Tier I indicators where possible, as they are standardized, robust, and cost-effective; at minimum, include both structural and functional indicators
Holistic integration	Combine biological indicators with chemical and physical soil properties, and interpret results in relation to local conditions (e.g. soil type, climate, land use, management)
Monitor changes over time	Focus on tracking trends rather than fixed thresholds in the short term, due to limited baseline data; thresholds can be developed as datasets improve

Source: Based on the EJP SOIL policy brief by Mocali et al. (2025).

Invest in soil biodiversity and subsoil monitoring

Given the near-total absence of long-term soil biodiversity monitoring data at the EU scale, dedicated EU-level funding is needed for: standardised eDNA and HTS-based soil biodiversity monitoring at a representative subset of LUCAS and national network sites; development of agreed Essential Soil Biodiversity Variables; and integration of soil biodiversity indicators into CAP monitoring and evaluation frameworks.

Support long-term financial sustainability of monitoring infrastructure

Soil monitoring systems cannot function on project-cycle timeframes. Policy should establish dedicated, multi-year financing instruments – analogous to the EU's long-term investment in Copernicus – for national SMNs, the EUSO/ESDAC infrastructure, and the Mission Soil Living Lab data continuity. Carbon and biodiversity market mechanisms should be explicitly designed to cross-subsidise public soil monitoring infrastructure, linking 'Measure, Report, Verify' requirements to the broader public monitoring network.

Strengthen governance coordination and knowledge translation

Policy should require multi-level governance coordination – from EU to MS to regional to farm level – in national soil monitoring plans, with explicit mechanisms for translating monitoring outputs into actionable guidance for land managers, insurers, and environmental authorities. Soil advisors and knowledge brokers, as proposed within the Mission Soil framework, should be supported through CAP advisory services to bridge the documented gap between monitoring evidence and on-ground practice (Thorsøe et al. 2023).

4.4.5. A call for continued investment in soil monitoring, mapping, and data collaboration

Soil monitoring and mapping are not a one-time scientific exercise – they are a long-term, evolving public infrastructure that underpins biodiversity protection, food security, climate resilience, and land use governance. Europe has made historically significant investments in soil knowledge through LUCAS, ESDAC, the EUSO, and now Mission Soil; but these investments remain fragile if they are not embedded within stable, long-term financing commitments that outlast individual projects and political cycles.

The scientific community calls upon EU institutions, MS governments, and funding agencies to:

- **Maintain and expand long-term SMNs** – including LUCAS, national SMNs, and Mission Soil Living Labs – with guaranteed continuity of measurement protocols, sampling frequencies, and data archiving that enable meaningful detection of decadal trends.
- **Invest in soil mapping at finer spatial resolutions**, prioritising currently under-represented areas including urban soils, peatlands, sub-Mediterranean drylands, and coastal zones facing salinisation – all areas of rapidly increasing management relevance under the climate change.
- **Sustain and expand the ESDAC and EUSO** as the EU's primary open soil data infrastructure, ensuring that advances in Earth Observation, citizen science, and Living Lab monitoring feed continuously into an integrated, policy-ready soil health evidence base (Panagos et al. 2024a).
- **Foster international data collaboration** – including through the GSP, FAO's Inter-governmental Technical Panel on Soils, and bilateral agreements with major soil science nations – to enable cross-validation of EU monitoring approaches and contribution to global soil health assessments (Smith et al. 2024).
- **Invest in the human capital** of soil monitoring – training the next generation of soil scientists, Remote Sensing specialists, and data engineers capable of operating hybrid monitoring frameworks – recognising that technological capacity means little without the scientific expertise to calibrate, validate, and interpret it.

As Smith et al. (2024) emphasise in their comprehensive review of the status of the world's soils, available BMPs and monitoring tools are sufficient to limit or mitigate major soil threats – but their effectiveness depends entirely on whether policies to protect and enhance soils are put in place, adequately resourced, and consistently enforced. Soil science has generated the knowledge needed to act. What remains is the political will, institutional commitment, and sustained investment to translate that knowledge into practice at the scale and speed that the European soil challenge demands.

4.5. Concluding remarks

Soil monitoring has evolved from periodic and largely descriptive assessments toward a dynamic, increasingly integrated system capable of supporting real-time, adaptive soil governance. This shift reflects both technological progress and a broader conceptual transition from documenting degradation to actively guiding restoration and resilience-building. Contemporary soil monitoring systems now combine conventional field surveys with Earth Observation, proximal sensing, digital soil mapping, and AI, enabling unprecedented spatial and temporal resolution in the assessment of soil health. The establishment of harmonised indicators and monitoring obligations under the SMRD marks a pivotal step in institutionalising this transformation across the EU. Equally important is the emergence of participatory monitoring approaches, including citizen science and Living Labs, which broaden the evidence base while strengthening stakeholder engagement. Nevertheless, major challenges persist, particularly regarding methodological standardisation, long-term funding, uncertainty communication, and the integration of diverse monitoring networks across scales. To fulfil its transformative potential, soil monitoring must move beyond passive observation and function as an operational early-warning and decision-support system that enables preventive action, evaluates policy effectiveness, and supports adaptive land management. In this sense, monitoring is no longer simply a technical activity – it is becoming a cornerstone of resilient and accountable soil governance.

5. Changes in soil literacy and societal engagement

5.1. Introduction

Achieving healthy soils across Europe by 2050 – the aspirational ambition of the EU Soil Strategy for 2030 (see section 2.2.5.5) and the SMRD (see section2.2.6) – require more than robust soil policy, scientific advances, technological innovation, and the widespread adoption of sustainable soil management practices. It will also demand a profound cultural shift in the way societies perceive and value soils. Soils are among the most complex and least visible components of the natural environment, yet they underpin virtually every dimension of human well-being, from food security and climate regulation to biodiversity and public health (Brevik et al. 2017; Keesstra et al. 2016). Despite this centrality, soils remain poorly understood by the general public and are consistently underrepresented in educational curricula, media discourse, and political debate (Bouma et al. 2012; Lobry de Bruyn and Prager 2024). Addressing this gap requires not only better communication of scientific knowledge but a systemic strengthening of societal awareness of the role of soils, and of soil literacy[83].

Current soil policy making in the EU has traditionally followed a predominantly top-down[84] approach, with limited active involvement of stakeholders. However, addressing soil degradation effectively requires a transition toward more inclusive and systemic governance frameworks that integrate socio-economic, cultural, and behavioural dimensions (Löbmann et al. 2022). In this context, soil literacy emerges as an enabling factor, supporting not only the dissemination of expert knowledge but also its translation into shared understanding and collective action. The successful implementation of soil-related policies depends on the active engagement of multiple actors: citizens, in their role as consumers; farmers and land managers, as primary stewards of soil resources; and businesses operating within land-based value chains. Strengthening synergies across sectors and fostering co-creation processes can facilitate gradual but meaningful changes in both practices and business cultures.

The need to enhance soil literacy is particularly urgent in contemporary societies, where urbanisation (Antrop 2004) and the industrialisation of agri-food systems have increasingly distanced citizens from soil. This disconnection contributes to consumption patterns that drive soil degradation, including unsustainable agricultural intensification and pollution from sources such as packaging and textile production. Improving soil literacy can help bridge this gap by enabling individuals to better understand the links between their consumption choices and soil health, thereby supporting a transition toward more sustainable behaviours, such as reduced management intensity and the adoption of agroecological practices (Wezel et al. 2020).

83 The capacity of individuals and communities to understand, interpret, and act upon soil-related information in ways that support responsible stewardship and sustainable land use.

84 The commonly used distinction between 'bottom-up' and 'top-down' approaches is often overly simplistic when applied to the integration of soil science into real-world projects. In practice, communication and knowledge exchange among scientists, entrepreneurs, public authorities, NGOs are far more complex and multidirectional. Interactions do not follow a linear or hierarchical pattern but instead vary significantly depending on the specific context, stakeholders involved, and project objectives. This complexity can create coordination challenges, hinder effective knowledge transfer, and obscure roles and responsibilities, ultimately limiting the efficiency of integrating soil expertise into practical decision-making and implementation processes (Bouma et al. 2011).

Scientists and policymakers have a critical role in increasing public awareness of the importance of soil health for the production of high-quality, nutritious, and safe food, as well as for human health more broadly (Rojas et al. 2016). Given that approximately 95% of global food production is directly or indirectly dependent on soils (Panagos et al. 2016; Montanarella and Panagos 2021a), the centrality of soils in sustaining human well-being is evident. However, the effectiveness of soil-related policies may depend not only on legal and institutional arrangements but also, in some cases, on the extent to which societies recognise soils as living systems, thereby introducing an ethical dimension into human–soil relationships (Albaladejo et al. 2021). In this context, strengthening societal awareness can foster a shift in perception whereby more individuals identify themselves as soil stewards and responsible land managers. This evolving sense of shared responsibility contributes to a collective ownership of soil resources and encourages active engagement in efforts to restore, protect, and sustain soils over the long term.

At the same time, the growing involvement of the private sector highlights the economic dimension of soil literacy. Partnerships among farmers, industries (e.g. food, beverage, and textiles), and retailers increasingly recognise the value of healthy soils as a foundation for sustainable and resilient value chains (Bouma et al. 2012). These collaborations promote practices that reduce the soil footprint of production systems and align economic incentives with environmental sustainability. Rising demand for organic products further illustrates how informed consumer choices – rooted in greater awareness of soil-related issues – can reinforce this transition (Casagrande et al. 2016), although policy frameworks such as the European Green Deal and the F2F Strategy have also played a significant role in driving the expansion of organic farming.

In this broader perspective, soil literacy extends beyond knowledge acquisition, functioning as a catalyst for behavioural change, cross-sectoral collaboration, and the reorientation of both policy and market systems toward sustainable soil management. Against this backdrop, the present chapter examines how soil literacy has evolved in Europe over the past decades, documents the key initiatives and activities that have progressively strengthened public awareness and understanding of soils. It discusses the specific role of the Mission Soil in advancing soil literacy through research, education, and stakeholder engagement. Finally, it identifies what is needed to accelerate this transition in the coming decades, ensuring that soil literacy becomes a genuine foundation for the cultural shift required to achieve healthy soils by 2050.

5.2. Strengthening soil literacy in the EU

5.2.1. Policy frameworks

5.2.1.1. The CAP and knowledge systems: institutional pathways for soil literacy

The CAP Network and its associated frameworks (**Table 11**) provide a platform for knowledge exchange across the European agri-food sector, strengthening the links between knowledge generation, transfer, and application (Knierim et al. 2015). Collectively, these initiatives contribute – directly or indirectly – to the development of soil literacy by enhancing awareness, facilitating knowledge co-creation, and supporting the adoption of sustainable soil management practices.

Table 11. Key CAP-related initiatives and their contribution to soil literacy in the European agricultural sector.

Initiative	Core function	Contribution to soil literacy	Link
Agricultural Knowledge and Innovation Systems (AKIS)	Integrates farmers, researchers, advisors, and authorities into a knowledge exchange system	Translates scientific knowledge into practical understanding of soil processes and management	https://eu-cap-network.ec.europa.eu/support/innovation-knowledge-exchange-eip-agri/akis_en
EU CAP Network	Facilitates networking, knowledge sharing, and dissemination of best practices	Raises awareness of soil health through peer learning and exchange of soil-related innovations	https://eu-cap-network.ec.europa.eu/index_en
European Innovation Partnership for Agricultural Productivity and Sustainability (EIP-AGRI)	Supports multi-actor innovation through Operational Groups addressing practical challenges	Enhances experiential learning on soil management through co-creation and field-based innovation	https://eu-cap-network.ec.europa.eu/support/innovation-knowledge-exchange-eip-agri_en
Farm Advisory Services	Provides advisory support, training, and technical guidance to farmers	Converts policy and scientific knowledge into actionable practices, improving soil-related decision-making	https://agriculture.ec.europa.eu/cap-my-country/cap-strategic-plans/fas_en
CAP instruments (conditionality, eco-schemes)	Links financial support to compliance with environmental and soil-related practices	Promotes learning-by-doing and increases awareness of soil functions and degradation risks	–

Source: JRC analysis.

5.2.1.2. The European Skills Agenda

The European Skills Agenda, launched in 2020, constitutes a central pillar of the EU's strategy to support the green and digital transitions through investment in human capital. It aims to improve the relevance and quality of skills and ensure that education and training systems are aligned with evolving labour market needs. Particular emphasis is placed on 'green skills', which include competencies related to sustainable resource management, environmental protection, and climate adaptation.

Building on this framework, the Pact for Skills fosters large-scale partnerships among industry, public authorities, education providers, and social partners to address skills gaps. It promotes collaborative approaches to training and workforce development, encouraging stakeholders to invest in skills that support sustainability and innovation. Although not specifically focused on soils, the Pact facilitates the integration of environmental competencies into sectoral training programmes, including those relevant to agriculture, land-based industries, and the bioeconomy. By

strengthening cooperation across sectors, it helps create a more coherent and responsive skills ecosystem capable of supporting the EU's sustainability objectives.

Together, these initiatives contribute to the advancement of soil literacy by enhancing the knowledge base and skillsets of actors involved in land management and related value chains. By embedding soil-related competencies within broader green skills frameworks, they support the development of both technical understanding (e.g. soil functions, ecosystem services) and operational capacities (e.g. sustainable practices, resource efficiency).

For example, training programmes developed in the context of carbon farming and ecosystem restoration increasingly require participants to understand soil health indicators, SOC sequestration, and monitoring methodologies. These competencies enable land managers not only to implement sustainable practices but also to assess and document their environmental outcomes, thereby connecting soil literacy with emerging policy and market mechanisms that reward sustainable land stewardship.

In this sense, soil literacy is reinforced not only through awareness but through professional training, advisory systems, and lifelong learning pathways. Such skills-oriented policies play a crucial role in equipping stakeholders with the capacities needed to interpret, apply, and act upon soil-related knowledge in diverse socio-economic contexts.

5.2.2. Networks and partnerships

Over the past decades, a wide range of networks, partnerships, and collaborative platforms have emerged across the EU to promote soil awareness, strengthen knowledge exchange, and support the development of soil literacy. These initiatives differ in their institutional character, governance structure, target audiences, and geographical scope, ranging from local and regional civil-society networks to European and international partnerships involving public authorities, research organisations, educational institutions, and non-governmental actors. Collectively, they have contributed to connecting scientific knowledge with policy processes, educational activities, stakeholder engagement, and practical land-management actions.

Given the large number and diversity of initiatives, the present section focuses on a selected set of examples that are particularly relevant to the European soil literacy landscape. The initiatives discussed below were chosen on the basis of their European or transnational scope, their explicit contribution to awareness-raising and soil education, their institutional relevance within broader soil governance frameworks, and their demonstrated role in facilitating knowledge exchange among multiple stakeholder groups. While not exhaustive, these examples illustrate the variety of approaches through which soil literacy has been promoted and institutionalised across Europe.

5.2.2.1. European Network on Soil Awareness

The European Network on Soil Awareness (ENSA), established in 2013, represents one of the first coordinated efforts at the European level explicitly dedicated to promoting soil literacy. ENSA is a typical example of bottom-up approach from the local to the national level in raising soil awareness (Bouma et al. 2012). Operating as a voluntary network of organisations, ENSA served as a platform for sharing best practices, educational resources, and awareness campaigns across European countries, connecting local initiatives with national soil policy frameworks. It played a meaningful role in fostering public engagement with soil health issues, supporting moreover the exchange of knowledge between scientists, educators, and policymakers. Its collaborative approach exemplified how civil society actors can drive soil literacy without formal legislative mandates, building

horizontal networks of knowledge and engagement across institutional boundaries. Its legacy continues to inform current soil awareness efforts through the organisations it collaborated with, including the European Land & Soil Alliance (ELSA) (https://www.bodenbuendnis.org/en/) and the European Soil Bureau Network Working Group on Soil Awareness and Education (UNEP 2007). ENSA's work has also contributed to shaping the soil literacy dimension of subsequent EU initiatives, including the Mission Soil.

5.2.2.2. European Soil Partnership

The European Soil Partnership (ESP), established under the framework of the FAO GSP (see section 2.2.13) represents the regional implementation mechanism for soil-related actions in Europe. Among its six Action Areas (AA), AA4 – 'Promote Awareness Raising and Advocacy' – is specifically dedicated to strengthening soil literacy across the region. AA4 focuses on enhancing communication, promoting education and training, and fostering stakeholder engagement to increase awareness of soil functions and the need for sustainable soil management.

Activities under AA4 include the development of educational resources, organisation of workshops and training programmes, and support for awareness campaigns at various levels of engagement (Regional, Subregional[85]) and National[86] – Slovenia, Slovakia, Ukraine, Portugal, and Italy have established National Soil Partnerships within the ESP so far. The ESP also collaborates with academic institutions, governmental bodies, and Non-Government Organizations (NGOs) to integrate soil education into formal and informal learning systems. Through these actions, it aims to build capacity among different stakeholder groups, from policymakers and land managers to university students, secondary school pupils and the public.

By aligning regional efforts with global frameworks such as the SDGs and the UNCCD, the ESP contributes to the coherence and scaling of soil literacy initiatives. Its role is particularly important in ensuring that scientific knowledge is effectively translated into practice and that awareness-raising activities are embedded within broader policy and governance processes.

5.2.2.3. European Land & Soil Alliance

The European Land & Soil Alliance (ELSA), also known as the 'Bodenbündnis', is a transnational civil society network of municipalities and regions committed to the sustainable use and protection of soils. Established in 1992, it represents one of the earliest initiatives linking soil awareness to local governance and community engagement. Its core activities include promoting sustainable land-use practices, limiting land take and soil sealing, encouraging brownfield redevelopment, and integrating soil considerations into spatial planning. Member organisations from Germany, Austria, Italy, Czechia, Bulgaria, and other European countries collaborate through joint declarations, educational initiatives, and outreach actions supporting soil protection policies.

ELSA's distinctive contribution lies in its focus on the local and regional governance scale, where direct interaction with citizens and land users enables tangible behavioural change. By linking scientific knowledge with participatory processes, the network fosters a culture of soil stewardship that complements top-down regulatory frameworks. It also maintains connections with ENSA and

85 https://www.europeansoilpartnership.org/european-soil-partnership/subregional-partnerships

86 https://www.europeansoilpartnership.org/european-soil-partnership/partners/national-soil-partnerships

the ESP, reinforcing its role within the broader European soil literacy landscape. This emphasis on local ownership reflects a participatory model of environmental governance in which soil literacy is developed as an active, community-embedded capacity rather than a passive transfer of expert knowledge (Bouma et al. 2012).

5.2.3. Knowledge, data and awareness infrastructure

5.2.3.1. The role of the EUSO in promoting soil literacy

The EUSO plays a central role in advancing soil literacy by actively promoting citizen engagement, awareness-raising, and societal understanding of soils as a fundamental natural resource. Within this framework, EUSO moves beyond traditional scientific communication and positions soil knowledge as a shared societal responsibility, aiming to bridge the gap between soil science, policy, and citizens.

A core assumption underpinning EUSO's citizen engagement strategy is that soil degradation is closely linked to low public awareness of the value and functions of soils. As highlighted in its citizen engagement initiatives, soils are generally undervalued in society and underrepresented in education systems, which contributes to insufficient investment in soil protection and weak political prioritisation of soil health. EUSO therefore seeks to address this gap by promoting soil literacy as a key driver of behavioural and policy change.

To achieve this, EUSO develops and supports a wide range of initiatives that translate complex soil knowledge into accessible, actionable information. These include stakeholder forums, educational resources, citizen science initiatives (where the public is directly involved in monitoring soil health, thereby strengthening both awareness and data collection), soil dashboards, and targeted communication campaigns. A key element is the emphasis on tailored messaging, helping different audiences – ranging from citizens and schools to policymakers and land managers – understand how their actions influence soil health and ecosystem services.

A flagship activity in this context was the '*Advancing Soil Literacy*' workshop, which brought together scientists, educators, policymakers, and civil society actors to explore how soil awareness and education in tackling soil degradation can be strengthened across Europe. These exchanges aimed to identify best practices and develop a roadmap for embedding soil literacy more deeply into education, policy, and public discourse. The workshop on March 13–14, 2025, hosted in Ispra, Italy, focused on sharing best practices and exploring innovative approaches – such as citizen engagement, co-creation, and locally tailored communication – to enhance soil knowledge and its societal relevance. Discussions emphasized that improving soil literacy requires moving beyond communication toward participatory and interdisciplinary actions that connect science with communities and policy. A list of the projects[87] and initiatives presented during the workshop is available in the official workshop materials and presentations site.

Overall, the role of EUSO in promoting soil literacy can be summarized as a knowledge-to-action interface: it translates scientific understanding of soils into societal awareness, encourages public

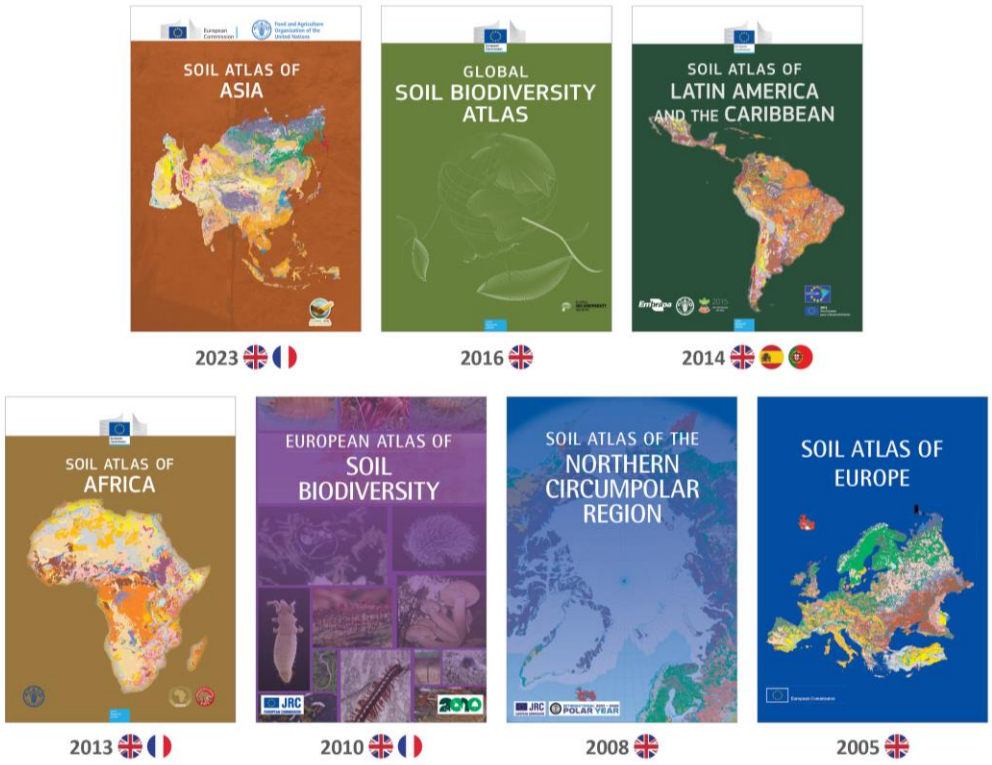
87 HoliSoils (https://holisoils.eu/), HuMUS (https://www.humus-project.eu/), TERRASAFE (https://terrasafe.eu/), PREPSOIL (https://prepsoil.eu/), LOESS (https://loess-project.eu/), SOLO (https://soils4europe.eu/), SoilTribes (https://soiltribes.eu/), SOILSCAPE (https://soilscape.eu/)

participation, and supports the EU's broader Soil Strategy and Mission 'A Soil Deal for Europe.' Through these efforts, EUSO contributes to fostering a culture in which soils are recognized as a vital component of environmental sustainability and human well-being.

5.2.3.2. Soil Atlases

The JRC has made a substantial contribution to soil literacy in Europe through the development, in collaboration with many partners, of the *Soil Atlas of Europe* (Jones et al. 2005b) and subsequent thematic atlases, e.g. the *European Atlas of Soil Biodiversity* (Jeffery et al. 2010), the *Soil Atlas of the Northern Circumpolar Region* (Jones et al. 2009), the *Soil Atlas of Africa* (Jones et al. 2014) (**Figure 16**). These publications represent key knowledge dissemination tools aimed at translating complex scientific information into visually accessible and engaging formats for a wide audience.

Figure 16. Soil Atlases.



Source: JRC analysis.

The *Soil Atlas of Europe* was one of the first comprehensive efforts to communicate the diversity, functions, and threats to soils across Europe in a user-friendly manner. Combining scientific data with maps, illustrations, and explanatory texts, the atlas has been widely used in educational contexts, policy discussions, and public outreach activities. Similarly, the *European Atlas of Soil Biodiversity* brought unprecedented public and scientific attention to the richness and vulnerability of soil ecosystems, fostering recognition of soil as a living system rather than an inert substrate.

By making soil information more accessible and understandable, the Soil Atlases have played a crucial role in bridging the gap between scientific research and societal awareness. Their widespread dissemination – both in print and through open digital access (Selvaradjou et al. 2007; Panagos et al. 2011) – have contributed to fostering a shared understanding of soil-related

challenges and have supported the integration of soil considerations into broader environmental and educational agendas.

5.2.4. Advancing soil literacy through R&I

5.2.4.1. Mission Soil under Horizon Europe

Increasing soil literacy[88] among citizens, practitioners, and policymakers is one of the central objectives of the EU Mission 'A Soil Deal for Europe'. The Mission Soil implementation plan defines soil literacy as 'both a popular awareness about the importance of soil, and specialised and practice-oriented knowledge related to achieving soil health' (https://mission-soil-platform.ec.europa.eu/resource-library/mission-soil-implementation-plan). The Mission combines an ambitious transdisciplinary R&I programme with increased soil literacy and communication efforts to engage with citizens, recognising that scientific progress alone is insufficient without a corresponding rise in public understanding and stewardship capacity. Soil literacy is increasingly understood as a prerequisite for the behavioural and governance changes needed to halt soil degradation across Europe (Keesstra et al. 2016; Orgiazzi et al. 2016b). To this end, the Mission pursues a multi-pronged strategy: funding R&I projects that embed education and outreach, supporting Living Labs and Lighthouses as place-based demonstration sites, and mobilising broad societal engagement through dedicated initiatives and events such as the annual European Mission Soil Week.

A key instrument for community-building and commitment is the Mission Soil Manifesto, launched on 18 April 2023, which calls for action to respond to the urgent need to protect and improve soil health in Europe and beyond, and brings together regional and local policymakers, stakeholders, and citizens into a vibrant community that cares for soil health. The Manifesto can be signed by a wide range of actors – from municipalities and research institutions to schools, NGOs, and individuals – making it an accessible entry point for those wishing to express solidarity with the Mission's goals and join a growing community of practice. Progress across these engagement dimensions is tracked through the Mission Soil Dashboard, which visualises, through interactive graphs and maps, a series of indicators – including the number of individual signatories of the Manifesto – to monitor activities related to the Mission's objectives. Together, these instruments reflect a deliberate effort to translate scientific knowledge into shared societal values around soil health.

5.2.4.2. Mission Soil-funded projects

The Horizon Europe-funded projects discussed in this section represent a core vehicle through which the Mission operationalises its soil literacy agenda. Drawing on frameworks from environmental education and science communication, these projects develop tools, curricula, and participatory methodologies that target diverse audiences, from schoolchildren to land managers and local authorities. The Mission's Living Labs and Lighthouses play a particularly important role, pioneering, showcasing, and accelerating the transition to healthy soils through ambitious actions within specific territorial settings, thereby grounding abstract scientific concepts in locally relevant

88 Encompasses knowledge of soil functions, threats, and management options.

experience and practice. The following subsections present selected projects that illustrate how R&I under Mission Soil is advancing soil literacy across Europe.

This approach is consistent with the broader recognition that sustainable soil management requires not only scientific knowledge of soil quality and ecosystem functions but also greater societal awareness and stakeholder engagement (Robinson et al. 2012; Bünemann et al. 2018).

The CURIOSOIL project

CURIOSOIL (https://curiosoil.eu/) (2024–2028) places soil literacy at the centre of societal transformation. It promotes experiential and participatory learning through educational resources (e.g. curriculum integration materials, 'soil curiosity' toolkits, etc.), teacher empowerment (through training and professional development), and citizen engagement (creates knowledge production but also enhanced understanding of soil systems) activities. By fostering Communities of Practice and integrating soil into formal and informal education, the project strengthens soil literacy as a socially embedded and practice-oriented capacity linking science, education, and public awareness.

The ECHO project

ECHO (https://echosoil.eu/) approaches soil literacy as a differentiated (stakeholders exhibit distinct knowledge profiles and learning needs; they begin with heterogeneous levels of soil-related knowledge), dynamic, and context-dependent (practical and/or systematic or scientific) capacity, varying across stakeholder groups and evolving through participation. Through citizen science, training, and co-creation processes, it enhances participants' ability to understand soil systems, but also to interpret and apply soil-related information. The project highlights that soil literacy develops progressively through engagement, combining knowledge acquisition with experiential learning and data interpretation skills across diverse actors (Peiro et al. 2024).

The PREPSOIL project

PREPSOIL (https://prepsoil.eu/) (2022–2025) supported the implementation of the EU Mission Soil by preparing the ground for Soil Health Living Labs and Lighthouses. The Living Labs concept plays a key role in coordinating knowledge production processes (McPhee et al. 2021), while the demonstration and exchange of innovations within and across Living Lab networks further facilitates the uptake of sustainable principles (Beaudoin et al. 2022). Its contribution to soil literacy lies in fostering stakeholder engagement, co-creation, and cross-sectoral dialogue, translating scientific knowledge into accessible and practice-oriented forms. It strengthened soil literacy as a shared capacity underpinning participatory soil governance.

Beyond its preparatory and coordination functions, PREPSOIL delivered measurable contributions to soil literacy and stakeholder engagement across Europe. By the end of the project, it had engaged more than 80 Communities of Practice across over 50 regions, organized more than 12 outreach activities in seven EU countries, and developed a multilingual Soil Knowledge Hub that recorded more than 27,000 visits. In addition, PREPSOIL built a social-media community of nearly 3,000 followers and developed participatory tools, networks, and knowledge-sharing platforms that supported the implementation of the Mission Soil framework (https://cordis.europa.eu/project/id/101070045/reporting).

The NATI0ONS project

NATI0ONS (https://nati00ns.eu/) (2022–2025) focused on accelerating the deployment of Soil Health Living Labs and Lighthouses through coordination and stakeholder mobilisation. It enhanced soil literacy by promoting participatory approaches, workshops, and multi-actor dialogue, fostering a

shared understanding of soil health challenges and strengthening stakeholders' capacity to engage in soil-related decision-making.

Beyond its coordination role, NATI00NS achieved substantial outreach across Europe by mobilising stakeholders around the objectives of the Mission Soil initiative and the development of Soil Health Living Labs. The project organised National Engagement Events in 42 countries during the first call cycle and in 44 countries during the second, creating opportunities for dialogue among scientists, policymakers, land managers, farmers, businesses, and civil society organisations. These activities were complemented by seven capacity-building webinars, two European matchmaking events, a dedicated helpdesk service, and a network of trained national mentors operating in 18 countries. Through these actions, NATI00NS provided guidance and support to prospective applicants, contributing to the submission of 44 proposals to the Mission Soil Living Lab calls in 2023 and 72 proposals in 2024. The project thus played a pivotal role in building awareness, fostering stakeholder participation, and strengthening the capacities required for the establishment of the first generation of Mission Soil Living Labs, thereby enhancing soil literacy not only as knowledge acquisition but also as a practical competence for engagement in soil-related innovation and governance (https://nati00ns.eu/news/together-soil-health-nati00ns-projects-journey-and-future-initiatives; https://cordis.europa.eu/project/id/101090738/reporting; https://mission-soil-platform.ec.europa.eu/project-hub/nati00ns; https://www.fao.org/family-farming/detail/en/c/1637670/).

The SOILL project

SOILL (https://www.soill2030.eu/) (launched in 2025) acts as a coordination and networking platform supporting the scaling of Soil Health Living Labs and Lighthouses across Europe. Through digital tools, matchmaking, and knowledge exchange, it facilitates collaboration among stakeholders. This network-based approach enhances soil literacy as a collective, practice-oriented process emerging from interaction, co-creation, and real-world experimentation.

The NBSOIL project

NBSOIL (https://nbsoil.eu/) (launched in 2023) focuses on advancing NBS for soil health and land restoration. Its contribution to soil literacy is primarily through capacity building and applied training, notably via the NBSOIL Academy (https://nbsoil.eu/soil-academy/), which equips advisors and practitioners with practical knowledge and skills. By linking theory with implementation, it strengthens soil literacy as an operational competence supporting sustainable soil management.

5.2.4.3. JRC SciArt: arts-based approaches to soil literacy

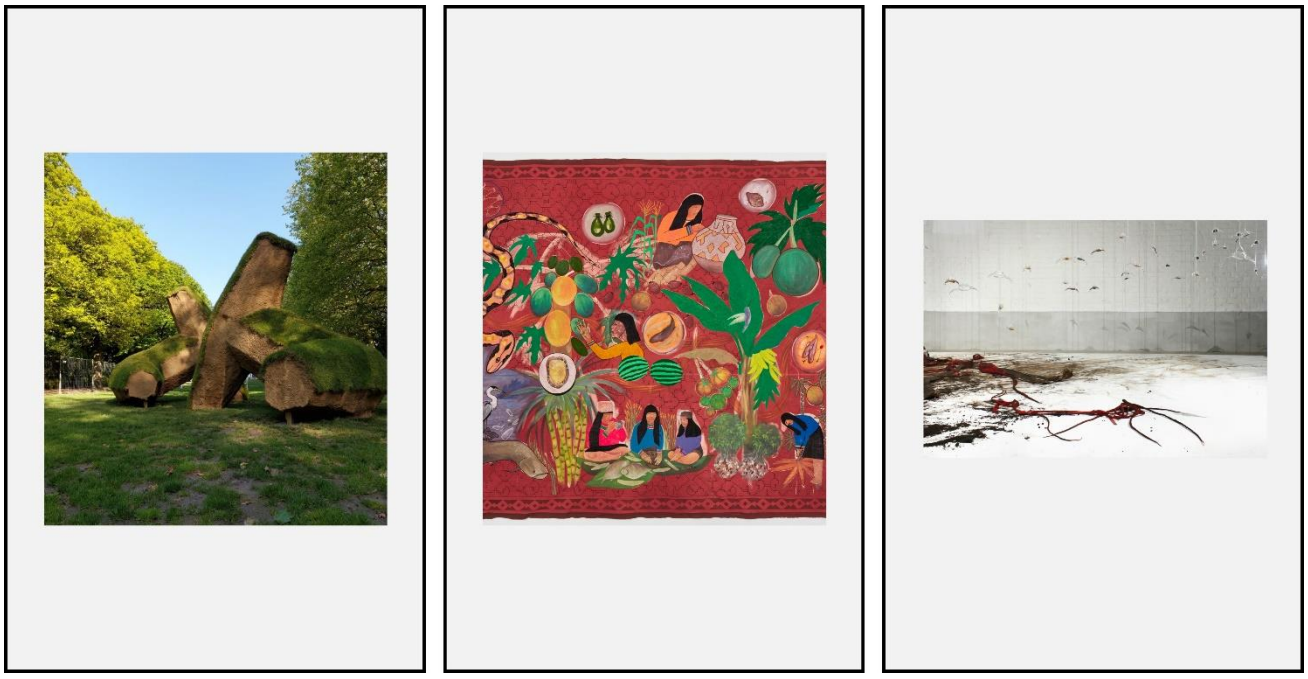
Soil doesn't sound like an obvious subject for art. It's beneath our feet, largely invisible, easy to take for granted. But that's exactly why artists have started paying attention to it – and why scientists have welcomed them in – the ground beneath us is in trouble, and it helps to have more than one language to talk about it.

Since 2016, the JRC has been bringing researchers and artists together to work on some of the issues that matter most to European policy, including the health of our soils. The results have been surprising. Projects like *Chthonics*[89] on soil as a living world of transformation, relation, and material

89 https://www.airchitecturalminds.com/projects-1/project-one-f5w4d-z9nem-s3jda-eyssk-73f62-tmxz9-g4t4z-sysd5

intelligence, *Earthbreakers*[90] on soil degradation, *Lament*[91] on postfire ecologies, *These Relations Are Forever*[92] on soil and agriculture, *Invisible Seeds*[93] on land use and biodiversity, etc., have approached soil not as a technical problem to be solved, but as a living world with its own stories (**Figure 17**).

Figure 17. JRC SciArt. From left to right: Earthbreakers (2024) by Ingrid Elsa Maria Ogenstedt, Invisible Seeds (2022–2024) by Gala Berger and Metsá Rama (Pilar Arce), Lament (2023) by Margherita Pevere.



Source: JRC, Earthbreakers (2024) by Ingrid Elsa Maria Ogenstedt, Invisible Seeds (2022–2024) by Gala Berger and Metsá Rama (Pilar Arce), Lament (2023) by Margherita Pevere.

What makes these collaborations matter is that they reach people that reports and data often don't. A published study on soil degradation is important, but it travels in certain circles. An artwork that makes you feel the loss of living soil — that moves differently. As both 'NaturArchy' (Benincasa et al. 2026) and Benincasa and Eeckels (2025) argue, bringing art into scientific and policy conversations isn't a soft add-on. It changes how we think, and sometimes, how we act.

Taken together, these initiatives illustrate a broader shift in European soil policy from knowledge dissemination towards participatory and practice-based learning. Although JRC SciArt projects are not Mission Soil research projects themselves, they reflect the same principles of engagement, co-creation, and societal connection that underpin Mission Soil's approach to soil literacy and stakeholder involvement. Soil literacy therefore emerges not as a static body of knowledge, but as a dynamic and socially embedded capacity developed through education, advisory systems, citizen science, arts-based approaches, and multi-actor collaboration. These complementary approaches

90 https://www.ingridogenstedt.com/work/earthbreakers

91 https://margheritapevere.com/lament/

92 https://jemmawoolmore.com/portfolio/these-relations-are-forever-2

93 https://science-art-society.ec.europa.eu/artworks/resonances-iv/riv-artworks-overview#invisible-seeds

contribute to creating the societal awareness and engagement required for the successful implementation of the Mission Soil objectives.

The SOILSCAPE project

A prominent example of integrating arts, culture, and soil literacy within Mission Soil is the SOILSCAPE project (Spreading Open and Inclusive Literacy and Soil Culture through Artistic Practices and Education) (https://soilscape.eu/). Funded under Horizon Europe's Mission Soil, SOILSCAPE explores how artistic practices, cultural initiatives, and creative communication can strengthen public understanding of soil and foster a deeper societal connection with soil protection. The project brings together soil scientists, artists, educators, civil society organisations, and citizens through a network of "Soil and Arts Orchestras" across Europe, using storytelling, visual arts, performances, and participatory activities to transform scientific knowledge into accessible and engaging experiences. By positioning soil as a cultural and societal concern rather than only a technical resource, SOILSCAPE directly supports Mission Soil's objective of improving soil literacy and mobilising citizens as active participants in the transition towards healthy soils.

5.3. Global and international soil literacy frameworks

The promotion of soil literacy has increasingly become a subject of international attention, leading to the establishment of numerous global and regional frameworks, partnerships, networks, and programmes that seek to raise awareness of soils and their essential functions for ecosystems, food security, climate regulation, and human well-being. These initiatives are led by a diverse range of actors, including intergovernmental organisations, international scientific bodies, development agencies, non-governmental organisations, and multi-stakeholder partnerships. Together, they contribute to strengthening soil knowledge, fostering capacity building, supporting policy development, and encouraging public engagement across different geographical and socio-economic contexts.

Given the large number of existing initiatives, this section highlights a selected group of global and international frameworks that have played particularly influential roles in advancing soil awareness and literacy worldwide. The examples were chosen based on their international reach, institutional significance, contribution to soil-related knowledge dissemination and capacity building, and their relevance to contemporary soil governance and sustainable land management agendas. While not intended to provide an exhaustive overview, the selected initiatives illustrate key approaches through which soil literacy has been promoted and integrated into global environmental and development frameworks.

5.3.1. FAO's contribution to global soil literacy

The FAO has played a central role in advancing soil literacy at the global scale, particularly through the establishment of the GSP in 2012 (see section 2.2.13). The GSP represents a voluntary, multi-stakeholder platform designed to promote sustainable soil management, improve soil governance, and enhance awareness of soil functions among policymakers and the public. One of its most influential normative contributions is the *Revised World Soil Charter* (FAO 2015b), which articulates key principles for soil stewardship and explicitly emphasises the need for education, outreach, and awareness-raising. Complementary instruments, such as the Voluntary Guidelines for Sustainable Soil Management (FAO 2017) (see section 2.2.13), further translate scientific knowledge into actionable recommendations accessible to a broad audience, including land managers and decision-makers. The GSP's Intergovernmental Technical Panel on Soils further advances soil literacy by

synthesising and communicating the state of global soil knowledge to policymakers and the public through flagship reports such as the *Status of the World's Soil Resources* (FAO 2015a).

Beyond normative frameworks, FAO has developed a suite of global initiatives that directly support soil literacy through data generation, knowledge sharing, and capacity development. These include the Global Soil Organic Carbon Map, the GloSIS and GLOSOLAN (see section 3.3.2), all of which contribute to improving access to harmonised soil information and strengthening technical competencies worldwide. However, one of the most impactful and visible mechanisms for advancing soil literacy has been FAO's sustained investment in global awareness campaigns – most notably the World Soil Day (WSD).

Officially endorsed by the UN General Assembly and implemented by FAO within the GSP framework, WSD – celebrated annually on 5 December – has evolved into a powerful global platform for science communication, public engagement, and policy advocacy. Since its institutionalisation following the International Year of Soils 2015[94], WSD has adopted a thematic approach, addressing critical soil-related challenges each year, such as soil pollution (2018), soil erosion (2019), biodiversity (2020), salinization (2021), and soil–water interactions (2023), soil monitoring and management (2024), and the importance of healthy soils for sustainable cities (2025). This thematic continuity ensures that complex scientific issues are translated into accessible narratives, fostering. both awareness and behavioural change.

Importantly, WSD goes beyond traditional dissemination of scientific knowledge by actively engaging diverse audiences through participatory and creative approaches. These include global competitions (photo, poster, book, and podcast contests), educational campaigns, and citizen-oriented activities that encourage direct involvement. As highlighted in FAO/GSP materials, WSD functions as a 'yearly call to action', mobilising stakeholders across scales – from schools and local communities to international organisations. The scale and impact of this initiative are remarkable. Over the past decade, WSD has reached billions of individuals worldwide through media coverage and digital campaigns, with thousands of events organised globally and extensive participation across more than 180 countries. This level of engagement demonstrates that soil literacy is no longer confined to academic or technical domains but is increasingly embedded within public discourse and global sustainability narratives. Moreover, the initiative fosters new partnerships and interdisciplinary collaboration, reinforcing the role of soils in addressing interconnected challenges such as climate change, food security, and ecosystem degradation.

In parallel, FAO has strengthened the science–policy interface through global symposia on key soil topics (e.g. SOC, soil pollution, soil biodiversity), which complement awareness campaigns by ensuring that the latest scientific knowledge informs both policy processes and public communication. Together, these efforts illustrate a comprehensive approach in which knowledge generation, policy frameworks, and societal engagement are tightly interconnected.

Through these combined actions, FAO has been instrumental in embedding soil literacy within global sustainability agendas, particularly in connection with the SDGs. By positioning soils as a cornerstone of food security, climate regulation, and ecosystem resilience, FAO not only advances

94 The International Year of Soils in 2015, declared by the UN General Assembly and facilitated by the FAO, marked a landmark moment in elevating soils to the global public agenda, resulting in hundreds of awareness events, educational campaigns, and policy commitments worldwide (FAO 2015c).

scientific understanding but also cultivates a more informed and engaged global society capable of supporting sustainable land management practices (Keesstra et al. 2016; Bouma et al. 2019).

5.3.2. UNCCD: advancing global soil awareness and stewardship

The UNCCD has been instrumental in promoting soil literacy within the broader framework of land degradation and sustainable land management. Since its establishment in 1994, the UNCCD has progressively shifted from a focus on desertification control toward a more integrated approach centred on LDN (Orr et al. 2017; Feng et al. 2022), formally adopted in 2015 as part of the 2030 Agenda for Sustainable Development and its SDG Target 15.3 (see § 2.2.13). By framing land degradation and soil degradation as a global development and security (food security, climate change adaptation, biodiversity conservation, etc.) challenge – rather than solely an environmental concern – the UNCCD has expanded the audience for soil literacy beyond scientific and agricultural communities to include development practitioners, civil society organisations, and the general public.

Flagship initiatives include the development of the LDN conceptual framework (https://www.unccd.int/land-and-life/land-degradation-neutrality/ldn-conceptual-framework), which provides a scientifically grounded and policy-relevant tool for assessing land condition and guiding restoration efforts. Concerning the EU, the framework has reinforced the urgency of soil governance by establishing internationally agreed benchmarks against which national and regional progress on land restoration can be measured. EU soil policies – including the Soil Strategy for 2030 and the SMRD – explicitly align with the LDN target, recognising the UNCCD framework as a normative reference for EU efforts. The Knowledge Hub (https://www.unccd.int/data-knowledge) and *Global Land Outlook* reports (UNCCD 2017, 2022) further contribute to soil literacy by synthesising scientific evidence on land degradation trends and their socio-economic consequences and translating it into accessible information for policymakers, practitioners, and the public. In addition, the Convention promotes stakeholder engagement through national action programmes and participatory approaches, recognising that effective land stewardship requires informed and empowered communities. The annual World Day to Combat Desertification and Drought (17 June) (https://www.un.org/en/observances/desertification-day), observed globally since 1995, has also contributed to recurring media and public attention on soil and land degradation, anchoring soil issues within a broader sustainability communication calendar.

5.4. Reframing soil literacy in Europe: from expert knowledge to societal capacity

The comparison between the 2012 (Jones et al. 2012) and 2024 (Arias-Navarro et al. 2024) 'State of Soils in Europe' Reports reveals a profound shift in how soil knowledge, understanding, and societal engagement are conceptualised and operationalised within soil governance. Taken together, the two reports trace an evolution from a technocratic, expert-driven framework to a more distributed, participatory, and system-oriented model in which soil literacy becomes a central enabling condition for policy effectiveness, coordination, and societal transformation. Yet to fully understand this shift, it is necessary to situate the 2012 assessment within a longer arc of change that began in the early 2000s – a period that saw the first concerted, institution-led efforts to bring soil science closer to society and to build awareness of soil's role in sustaining human well-being.

Already in the early 2000s, a series of landmark initiatives began to lay the foundations for what would later develop into a more explicit soil literacy agenda in Europe. Civil society engagement in

European soil governance began to gain institutional expression with the adoption of the Soil Manifesto issued by the Soil & Data Alliance of European Cities and Towns in 2000, which laid the foundation for the establishment of the ELSA (see section 5.2.2.3) in 2001, a transnational network of municipalities committed to soil protection as a public good. Through locally embedded initiatives and participatory approaches, ELSA pioneered bottom-up pathways for soil awareness and stewardship that complemented top-down regulatory frameworks. The publication of the *Soil Atlas of Europe* in 2005 (Jones et al. 2005b) was among the first systematic efforts to make European soil data accessible beyond the scientific community, translating technical mapping data into a visually compelling format designed for a broader readership that included educators, planners, and the public. A significant turning point was the adoption of the STS in 2006 (see section 2.2.2), which identified awareness-raising, knowledge development, and information exchange as important components of EU soil policy. Although the proposed Soil Framework Directive was ultimately not adopted, the STS played a crucial role in elevating soil issues within the European policy agenda and fostering more structured approaches to soil research, communication, and public engagement (Montanarella and Panagos 2021a). The *Atlas of Soil Biodiversity*[95] (Jeffery et al. 2010) brought unprecedented public and scientific attention to the living dimension of soils, helping to catalyse a cultural reframing of soil as an ecosystem rather than a substrate – a shift identified in the literature as fundamental to fostering a sense of stewardship and ethical responsibility (Albaladejo et al. 2021).

The period between 2012 and 2017 marked a substantial expansion of soil literacy initiatives, both globally and within Europe. At the international level, the establishment of the GSP by the FAO in 2012 (see § 2.2.13, § 5.2.1) represented a major milestone, providing a coordinated international platform for promoting sustainable soil management and raising awareness of soil functions. Key outputs, including the *Revised World Soil Charter* (FAO 2015b) and the *Status of the World's Soil Resources* report (FAO 2015a), played a pivotal role in translating scientific knowledge into accessible and policy-relevant information. With the proclamation of the International Year of Soils in 2015, soils received, for the first time, sustained attention within mainstream media and political discourse. The initiative mobilised governments, scientific institutions, schools, civil society organisations, and local communities worldwide through conferences, exhibitions, educational campaigns, and public outreach activities organised across more than 130 countries (FAO 2015b). The UNCCD's *Global Land Outlook* report (UNCCD 2017) and associated LDN conceptual framework (see § 5.2.2) further extended the normative reach of soil literacy by embedding soil protection within the global sustainable development agenda (Orr et al. 2017), providing European soil governance actors with an internationally legitimate reference framework for their awareness-raising activities. At the European level, the creation of the ENSA in 2013 (see section 5.2.2.1) connected civil society organisations, local authorities, and educational institutions across Europe in a voluntary platform for exchanging soil awareness resources, demonstrating that sub-national and non-governmental actors could be powerful drivers of soil literacy (Bouma et al. 2012).

In the following period (roughly between 2017-2020) the ESP (see section 5.2.2.2) strengthened regional coordination through its AA4 on soil awareness, advocacy, and education. At the same time, scientific contributions linking soils to ecosystem services and sustainability (Keesstra et al. 2016; Bouma et al. 2019; etc.) helped to consolidate the conceptual foundations of soil literacy. Importantly, this phase also saw increasing recognition of the societal dimension of soil

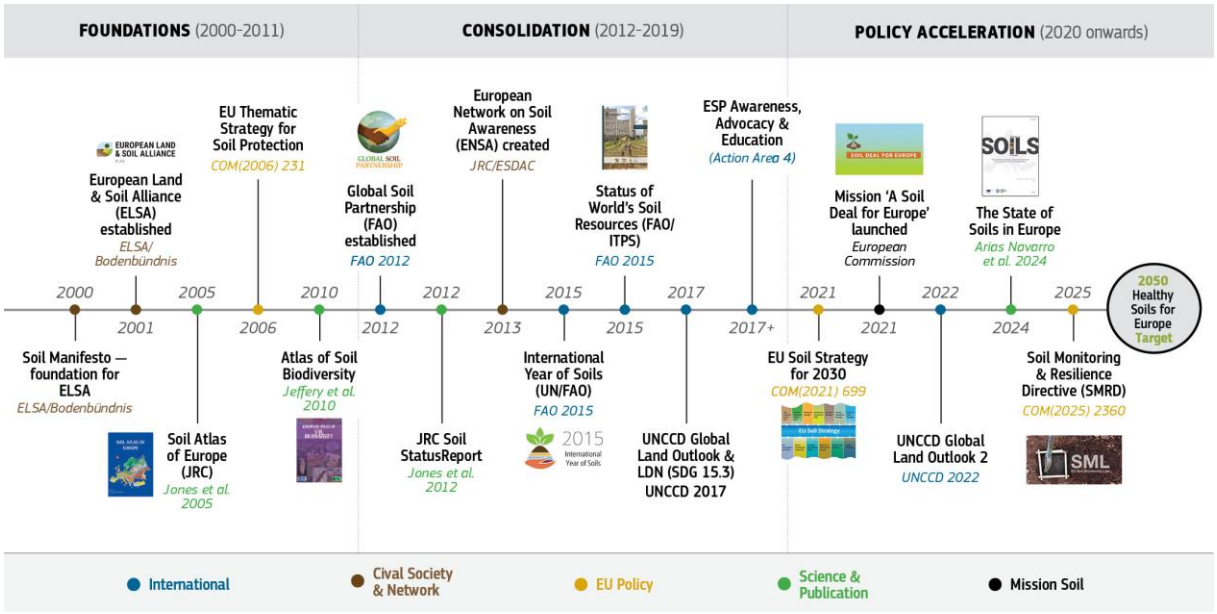
95 And the subsequent Global Soil Biodiversity Atlas (Orgiazzi et al. 2016b).

management. Soil literacy was no longer understood solely as knowledge acquisition but as a driver of behavioural change, influencing consumption patterns, land-use decisions, and policy support.

Since 2020, soil literacy has entered a new phase characterised by systemic integration into EU policy and governance frameworks. The European Green Deal and the EU Soil Strategy for 2030 have positioned soil health as a central pillar of sustainability transitions, explicitly linking it to climate neutrality, biodiversity restoration, and zero pollution objectives (Montanarella and Panagos 2021b). International assessments such as the second edition of the *Global Land Outlook* report (UNCCD 2022) further reinforced the urgency of strengthening societal awareness and transformative action toward sustainable land and soil management. A key innovation in this phase is the introduction of the Mission Soil[96], which represents the first EU initiative to explicitly include soil literacy as a core objective. By promoting Living Labs, citizen engagement, and co-creation processes, the Mission moves beyond traditional top-down communication models toward participatory and practice-oriented approaches. Soil literacy is thus embedded within a broader framework of social innovation, where knowledge generation and application occur through interaction among scientists, land managers, businesses, and citizens. At the same time, long-standing initiatives such as the ELSA continue to highlight the importance of local-level engagement and governance, demonstrating that effective soil literacy requires action across multiple scales – from global frameworks to regional networks and local communities.

The timeline of the major milestones shaping the evolution of soil literacy and awareness initiatives in Europe and beyond is presented in **Figure 18**.

Figure 18. Timeline of major international and European policy frameworks, initiatives, and knowledge platforms that contributed to the evolution of soil literacy and societal awareness from the early 2000s to the present.



Source: JRC analysis.

96 A new instrument under Horizon Europe, the EU framework programme for research and innovation 2021-2027.

The ‘State of Soils in Europe 2010’ Report (Jones et al. 2012), frames soil primarily as a biophysical resource governed through scientific knowledge and regulatory intervention. Soil degradation processes such as erosion, contamination, and organic matter decline are described in technical terms, and the role of knowledge is largely confined to expert communities – scientists, technical agencies, and policymakers. Within this framing, soil literacy is not explicitly articulated; it exists implicitly as a property of institutions rather than society. The public is largely absent from the conceptual landscape, and there is little emphasis on education, awareness, or participatory engagement. Knowledge functions primarily as a tool for protection: experts identify risks and institutions implement responses. Soil governance, in this sense, is structured as a top-down process grounded in scientific authority.

By contrast, the ‘State of Soils in Europe 2024’ (Arias-Navarro et al. 2024) Report reflects a more complex and integrated understanding in which soil is increasingly recognised as a living, multifunctional, and socially embedded system. Here, soil literacy emerges more explicitly as a distributed capacity that extends beyond expert communities to include stakeholders, land managers, and citizens. Knowledge is no longer solely a basis for regulation but becomes a mechanism for coordination across multiple actors operating at different scales. Farmers, planners, citizens, and institutions are all positioned as participants in soil-related processes, requiring shared understanding to align actions, navigate trade-offs, and contribute to common objectives.

This shift is closely linked to the rise of participatory and data-driven governance. The 2024 report strongly emphasises monitoring systems, digital tools, and citizen science as key components of soil policy implementation. In this context, soil literacy becomes both a precondition for meaningful participation and an outcome of it: individuals need sufficient understanding to contribute to data collection and interpretation, while engagement in monitoring activities further reinforces learning and awareness. This creates a reinforcing loop between literacy and participation, embedding knowledge production more deeply within society.

A more differentiated structure of soil literacy can also be inferred from the 2024 framing. Rather than a single unified concept, soil literacy operates across multiple layers. A functional dimension involves understanding basic soil processes and indicators; an operational dimension refers to the ability to apply practices and interpret monitoring data; and a civic dimension relates to participation in decision-making and evaluation of policy choices. Whereas the 2012 report implicitly assumes a high level of expert literacy concentrated within institutions, the 2024 framework distributes these competencies across society, reflecting a broader democratisation of environmental knowledge.

This evolution is also tied to a reconfiguration of how environmental risks are communicated and understood. In 2012, soil threats are scientifically well described but remain relatively abstract to non-experts. By 2024, processes such SOC loss, erosion, and salinisation are increasingly framed in relation to broader societal concerns such as the climate change, food security, and public health. Soil literacy thus becomes a mechanism for translating slow, diffuse environmental changes into socially meaningful narratives that can support behavioural change and policy acceptance.

A related transformation concerns temporality and visibility. Soil processes are inherently slow and often difficult to perceive directly. The 2024 emphasis on indicators, monitoring infrastructures, and digital platforms reduces this ‘invisibility problem’ by making trends observable within decision-relevant timeframes. Soil literacy, in this sense, becomes more evidence-based and time-sensitive, enabling stakeholders to engage with dynamic environmental information that was previously inaccessible or obscure.

Crucially, the two reports also reflect a shift in the role of institutions. In 2012, institutions function primarily as knowledge holders and regulators. By 2024, they increasingly act as intermediaries and facilitators, supporting knowledge co-production and translation across stakeholder groups. Advisory services, extension systems, NGOs, and citizen science platforms play a key role in making scientific knowledge accessible and socially usable. This redefinition of institutional roles highlights that soil literacy is not merely an individual attribute but depends on broader socio-technical infrastructures and communication systems.

Indeed, the 2024 assessment implicitly reframes soil literacy as an infrastructural phenomenon. Its development depends on the availability of data systems, digital tools, and transparent information flows. Where such infrastructures are weak, soil literacy cannot scale effectively, regardless of educational efforts. This marks a departure from the 2012 perspective, where knowledge is largely assumed to reside within institutions and is relatively detached from technological mediation.

Soil literacy therefore extends into a form of economic literacy, where stakeholders must understand how soil functions are translated into measurable, tradable, and policy-relevant units. For example, the increasing relevance of ecosystem service valuation and carbon farming implies that understanding soil processes is also necessary for participation in emerging bio-economies (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52025DC0960). At the same time, the 2024 assessment highlights that trust in soil governance must be actively constructed through transparency, participation, and shared knowledge production. Citizen science and open data initiatives thus serve not only technical purposes but also function as mechanisms for building epistemic trust in how soil knowledge is generated and applied.

Another important dimension that emerges more clearly in the 2024 perspective is inequality. Once participation takes a more central role in governance, differences in education, access to technology, land ownership, and institutional capacity become highly relevant. Soil literacy is therefore not evenly distributed and risks reinforcing existing social and spatial disparities if not carefully addressed. This stands in contrast to the 2012 framework, where such disparities are largely invisible because societal participation is not yet a core component of soil governance.

Across all these dimensions, the evolution from 2012 to 2024 reflects a broader paradigm shift. Soil governance moves from a predominantly technocratic model – where knowledge is concentrated and oriented toward regulation – to an integrated and participatory model in which knowledge is distributed, relational, and oriented toward coordination. Soil literacy emerges as a central enabling capacity within this new paradigm: it supports communication across actors, facilitates engagement with environmental risks, underpins data-driven monitoring systems, contributes to trust formation, and enables participation in both policy and emerging environmental economies.

Overall, the evolution of soil literacy in Europe reflects a transition from fragmented, expert-driven; institutionally confined awareness toward a more participatory model of soil stewardship, embedded within socio-ecological systems. Early efforts focused on understanding and documenting soil degradation, while subsequent phases emphasised communication, education, and policy integration. More recently, soil literacy has become a strategic tool for enabling behavioural change, supporting sustainable value chains, and fostering collective responsibility for soil resources. The key elements of this transformation are synthesised in **Table 12**.

Table 12. From technocratic knowledge to participatory governance: The evolution of soil literacy in Europe (2012–2024).

Dimension	2012 Report (Jones et al. 2012)	2024 Report (Arias-Navarro et al. 2024)
Conceptual framing of soil	Biophysical resource	Living, multifunctional, socio-ecological system
Role of knowledge	Expert-driven, diagnostic	Distributed, relational, enabling coordination
Soil literacy	Implicit, institutional	Explicit/operational, societal and multi-level
Primary actors	Scientists, policymakers	Farmers, citizens, advisors, institutions
Governance model	Top-down, technocratic	Participatory, networked, multi-actor
Function of knowledge	Risk identification and regulation	Coordination, engagement, co-decision-making
Public engagement	Largely absent	Central, through participation and co-creation
Monitoring and data	Limited, expert-controlled	Digital, real-time, participatory (citizen science)
Structure of literacy	Undifferentiated	Functional, operational, civic dimensions
Risk communication	Technical, abstract	Linked to climate, food, health narratives
Visibility of soil processes	Low (slow, invisible)	Enhanced via indicators and digital tools
Role of institutions	Knowledge holders, regulators	Facilitators, intermediaries, knowledge brokers
Knowledge infrastructure	Institutional, static	Socio-technical, data-driven, interactive
Economic dimension	Largely absent	Linked to ecosystem services, carbon markets
Trust and legitimacy	Assumed	Actively constructed (transparency, participation)
Equity considerations	Not addressed	Inequalities in access, capacity, participation

Source: JRC analysis.

5.4.1. Additional knowledge gaps and barriers to soil literacy in Europe

Thorsøe et al. (2023) conducted interviews with a broad range of stakeholders – including farmers, advisors, representatives of agricultural associations, NGOs, policymakers, and actors from the agri-food industry – all affiliated with the EJP SOIL project, and a more specialised group of soil researchers from universities, research institutes, and NGOs. The study aimed to assess the state of soil-related knowledge in the EU, its practical use, and existing gaps in relation to the sustainable soil management of farmlands.

Overall, stakeholders focused on the wider problems of the AKIS, emphasised systemic issues related to the effectiveness of knowledge exchange, particularly the limited capacity of existing structures to communicate soil management knowledge in a way that is accessible and usable for practitioners. They also highlighted that short-term research funding structures can undermine continuity in knowledge production, particularly where long-term monitoring activities are interrupted or discontinued.

More broadly, the study of Thorsøe et al. (2023) underscores a persistent disconnect between soil science and end users. Although soil research produces a substantial body of theoretical knowledge, this is often poorly aligned with farmers' practical needs, particularly in contexts where trade-offs between environmental, economic, and agronomic objectives must be balanced (Breure et al. 2024). As a result, many research outputs, datasets, and management recommendations remain difficult to translate into actionable practices (Bouma et al. 2012; Lobry de Bruyn et al. 2017; Hessel et al. 2022; Lobry de Bruyn and Prager 2024). This gap is further compounded by the fragmentation and uneven capacity of advisory services across regions, which limits their effectiveness in mediating between science and practice (Ingram and Mills 2018; Ingram et al. 2022; Labarthe and Beck 2022). The transformation of advisory systems across Europe – characterised by privatisation, decentralisation, and the emergence of pluralistic, commercially-oriented providers – has intensified these challenges, as it has generated advisory landscapes with highly variable levels of specialisation in soil management and uneven coverage across farm types and regions (Ingram and Mills 2019; Ingram et al. 2022).

Besides, communication of soil-related knowledge remains a significant challenge, as it is often not adapted to the needs of different societal groups (Bouma et al., 2012). Soil science education is typically highly technical, focusing on chemical, physical, and biological processes and soil classification, which is inaccessible to non-expert audiences. As a result, key societal functions of soils – such as their role in supporting human life, providing ecosystem services, and preserving cultural and geological heritage – remain under-communicated and poorly understood by the wider public. This contributes to limited societal awareness of soils as shared natural and cultural assets, despite the fact that all citizens are affected by and dependent on these functions (Lobry de Bruyn and Prager 2024). In addition, the lack of integration between soil science and social sciences further limits the translation of complex soil processes into meaningful, socially relevant information, reinforcing the gap between scientific knowledge and public understanding (Grant 2023; Trdlicova and Neilson 2025).

A key challenge in communicating soil-related issues lies in their temporal dimension, which complicates engagement with both policymakers and journalists. Media attention is typically triggered by sudden events such as landslides or other acute disasters, whereas most forms of soil degradation develop gradually over long-time horizons, often spanning decades – a dynamic that has been described as a 'quiet crisis' whose slow pace allows it to escape societal perception (Gomiero 2016). This slow, incremental nature makes soil problems less visible and less compatible with short-term communication cycles. Furthermore, structural mismatches exist between natural, agricultural, and policy timeframes: while agricultural production follows seasonal or annual cycles, policy processes are often limited to electoral periods of four years or less. These divergences create a spatial, temporal, and institutional disconnect that constrains effective communication and reduces the prioritisation of soil issues in policy and public discourse (Bouma et al. 2012).

A further challenge lies in the limited engagement of younger generations with soil-related issues. Despite the long-term nature of soil degradation and the need for sustained stewardship, there is insufficient emphasis on systematically cultivating interest, knowledge, and responsibility among youth (Lobry de Bruyn et al. 2017). Universities offering soil science programmes face considerable difficulty in recruiting students, many of whom are unaware the discipline exists (Brevik et al. 2022; Charzyński et al. 2022). This gap risks undermining the continuity of soil-related expertise and awareness over time, as future decision-makers, professionals, and citizens may lack the necessary understanding and motivation to address soil challenges effectively.

5.5. Future outlook and perspectives

Soil literacy and citizen involvement are expected to become central elements of soil policy in the EU, rather than complementary communication or awareness-raising activities. The impacts of the climate change on soils become more visible and locally experienced – through increased erosion damage, declining soil fertility, salinity-induced yield losses, and the degradation of soil biodiversity. These pressures interact with human-driven factors including, among others, market-driven production pressures, consumer demand patterns, agricultural intensification, mechanisation, land take and soil sealing, etc., amplifying soil degradation risks.

Within this context, a basic public understanding of soil functions, limits, and trade-offs becomes essential for effective soil governance. Soil literacy underpins public trust, policy legitimacy, and behavioural change, supporting long-term responsibility and stewardship of soil resources (EEA 2019). Beyond general awareness, future soil governance will increasingly require stakeholders to understand soil health indicators (EEA 2012; Kosmas et al. 2014; Borrelli et al. 2015, EUROSTAT 2024, etc.) and monitoring outputs, enabling them to interpret soil condition assessments and translate them into practical management decisions. This perspective is increasingly reflected in major EU soil policy frameworks. The EU Soil Strategy for 2030 recognises that protecting soil health requires not only regulatory measures but also informed land users and citizens, explicitly highlighting the role of awareness, education, and access to soil information. Similarly, the SMRD aims to improve the transparency and accessibility of soil data, supporting evidence-based decision-making at local, regional, and national levels. The Mission Soil further emphasises the need to enhance access to soil information, strengthen stakeholder participation, and foster societal ownership of soil protection objectives.

Digital tools and open soil-data platforms are expected to play a key role in this process through providing access to information on soil carbon stocks, erosion risk, land take and sealing, biodiversity, and soil contamination. EU initiatives such as the EUSO enable citizens, farmers, businesses, and local authorities to better understand soil conditions and trends (OECD 2019). For example, the EUSO Soil Degradation Dashboard estimates a range of soil degradation indicators, including nutrient surpluses and contamination by heavy metals, supporting the assessment of soil health status across Europe. At the same time, digitalisation is expected to facilitate the democratisation of soil information through interactive platforms, participatory mapping, and emerging AI–supported interpretation tools that allow non-specialists to engage with complex soil datasets. Soil literacy also plays an important role in shaping the conditions under which land managers adopt and implement sustainable management practices (Burnham et al 2023; Trdlicova and Neilson 2025).

Citizen science initiatives (Haklay 2013) are increasingly promoted within EU frameworks, such as local observations of surface erosion, soil sealing, and earthworm counts. When supported by appropriate quality assurance, training, and feedback mechanisms, these initiatives can complement official monitoring systems while strengthening public engagement with soil protection goals – while evidence on the relationship between soil literacy and land management behaviour is only beginning to emerge in soil science (e.g. Rossiter et al. 2015), related fields such as ecology have a much longer history of research on how knowledge, awareness, and values influence environmental decision-making and stewardship (e.g. Johnston et al. 2022). However, differences in soil literacy levels among regions, professional groups, and socio-economic contexts may influence policy effectiveness, requiring targeted capacity-building, inclusive communication strategies, and locally adapted knowledge transfer mechanisms.

Soil communication needs to become more targeted, interdisciplinary, and audience-specific (Bouma et al. 2012). This involves translating technical soil processes into accessible narratives that emphasise their tangible outcomes, such as food provision, climate regulation, and cultural heritage preservation. Strengthening collaboration between soil scientists and social scientists can support the development of more effective communication strategies tailored to different stakeholder groups. In parallel, the gap between expert knowledge and societal understanding can be bridged by integrating soil topics into i) education systems (e.g. primary/secondary level courses, fieldtrips, etc.), ii) communication tools (e.g. soil atlases, citizen science platforms, smartphone applications, etc.), iii) creating peer-to-peer communities[97] for practitioners to exchange insights and successful bottom-up soil management paradigms, and iv) valorising[98] good practices (https://data.europa.eu/doi/10.2777/704413). Long-term communication on soil issues should highlight the impacts of soil degradation not only through its environmental consequences but also by illustrating the economic trade-offs associated with different soil protection measures, including their costs and benefits (Bouma et al. 2011). With regards to outreach efforts, it is essential to reinforce the role of knowledge brokers – including agricultural extension officers, soil advisors, farmer cooperatives, Living Lab coordinators, and technical consultants – who maintain direct contact with practitioners, offering guidance and recommendations while acting as intermediaries between stakeholders and the scientific community (Efthimiou 2024).

The future effectiveness of soil governance will also depend on systemic and participatory approaches that actively involve citizens as consumers, farmers as custodians of soil resources, and companies operating in land-using sectors (https://data.europa.eu/doi/10.2777/282386; Ammann et al. 2025; Guerrieri et al. 2025). Their interaction can progressively reshape soil-management practices, consumption patterns, and business models, reinforcing the role of soil literacy in driving cultural and ethical change. Increasingly, public awareness and consumer demand are expected to influence market incentives, including certification schemes, carbon farming initiatives, and sustainability labelling systems that incorporate soil health criteria (Kragt et al. 2016). In this context, soil literacy contributes to establishing a social licence for sustainable management by strengthening societal acceptance of land-use practices and restoration measures. Another custodian perspective on land management is that the perception of soils as living systems introduces an ethical dimension to human–soil relationships and encourages broader recognition of shared responsibility for soil health. Furthermore, given that farmers hold valuable technical expertise and implementation skills (Crane 2010), involving them in transdisciplinary approaches[99] – particularly in co-creation and field-testing processes – can enhance the practical relevance of generated knowledge and lead to more applicable and realistic solutions (Thorsøe et al. 2023).

Overall, EU soil policies increasingly acknowledge that healthy soils cannot be achieved through legislation alone. Sustained investment in education, advisory services, institutional capacity, and youth engagement – aligned with the CAP and the European Green Deal – is necessary to ensure that soil literacy supports informed decision-making. The integration of soil education into formal curricula, vocational training, and farmer-to-farmer learning networks is expected to strengthen long-term societal engagement and intergenerational knowledge transfer. By strengthening societal

97 Physical or online, local or international.

98 Like the 'Soil of the Year' showcasing that takes place in Berlin, Germany, during the World Soil Day.

99 This hybrid model is known as ethnopedology (WinklerPrins and Sandor 2003).

awareness and participation, soil governance can more effectively support emerging instruments (e.g. carbon farming schemes, soil certification systems) translating knowledge and engagement into measurable environmental, economic, and social outcomes.

5.6. Concluding remarks

Achieving healthy soils by 2050 will require not only stronger policies, better data, and more sophisticated monitoring systems, but also a profound cultural transformation in how societies perceive and value soils. Soil literacy has emerged as a critical enabling dimension of this transition, bridging scientific understanding with behavioural change, public participation, and collective responsibility. Across Europe, initiatives led by the EUSO, the Mission Soil, educational networks, and citizen science programmes are helping to transform soils from an invisible environmental substrate into a visible and shared societal concern. This shift reflects an important conceptual evolution: soil literacy is no longer understood solely as the dissemination of knowledge, but as a dynamic social capacity that empowers individuals, communities, institutions, and markets to engage meaningfully in soil stewardship. As awareness grows, so too does the potential for more sustainable consumption patterns, improved land management practices, and stronger political support for soil protection. However, significant gaps remain, particularly in formal education, professional training, and the inclusion of diverse social groups in soil-related dialogue and decision-making. Strengthening soil literacy must therefore become a long-term strategic priority embedded across educational systems, policy instruments, and public communication efforts. Ultimately, the durability of Europe's soil transition will depend on whether society comes to recognise healthy soils not merely as an environmental necessity, but as a shared foundation for resilience, prosperity, and intergenerational responsibility.

6. Quantitative changes of soil degradation indicators[100]

6.1. Introduction

Several EU policy initiatives have been taken over the past decades to protect and restore soils (see Chapter 2). For instance, since 2003, the Good Agricultural and Environmental Conditions (GAEC) under the Common Agricultural Policy (CAP) have helped steer farming practices towards greater environmental sustainability. The CAP 2023-2027 includes requirements on soil protection and sustainable soil management, as well as eco-schemes supporting farmers to preserve natural resources and minimise the negative impact of agriculture on the environment. Also the European Green Deal has highlighted the importance of soil protection and the crucial role soils have in achieving some of its objectives, including mitigating climate change, halting the loss of biodiversity and achieving zero pollution (Montanarella and Panagos, 2021). Soil-related policy actions and ambitions are present in the strategies published as part of the European Green Deal, including the EU Biodiversity Strategy for 2030, the Zero Pollution Action Plan, and the Fit for 55 package. Major milestones for soil protection in the EU were the publication of the EU Soil Strategy for 2030 (see section 2.2.5.5), the entry in to force of the Soil Monitoring and Resilience Directive (SMRD, Soil Monitoring Law) (see section 2.2.6), and the Mission Soil (see section 2.2.12.1), all including the aspirational objective to reach healthy soils in the EU by 2050. These policy initiatives characterise soil health as the absence of significant anthropogenic degradation, adhering to the free-from-degradation principle (see e.g. Campbell et al., 2025). To evaluate the effectiveness of these policy initiatives in protecting and restoring soils, it is important to monitor how soils have evolved since the implementation of these various policy initiatives. Soil monitoring over time and studying changes in soil status can help to evaluate the impact of policy interventions and highlight the potential need for new or adapted policy actions.

The current state of soils in Europe has been well described (Arias-Navarro et al., 2024), and the current baseline of relevant soil degradation processes are documented and visualised in the EUSO Soil Degradation Dashboard using a range of EU wide datasets (Panagos et al., 2024b). Policy actions are tracked, such as those included in the European Green Deal (e.g. Marelli, Luisa et al., 2025; Paleari, 2026), in the CAP (European Commission, 2025b; Schievano, Andrea et al., 2025), and in the EU Soil Strategy for 2030 (e.g. Broothaerts et al., 2025), but the outcomes of the policy actions on the soil status are currently not clearly examined. Qualitative assessments suggest that most soil degradation processes have intensified over the last decades (Arias-Navarro et al., 2024). However, quantitative data on temporal changes over the state of soils across Europe are generally lacking. This is mainly due to different obstacles and challenges. Challenges to monitor and document such temporal changes include variations in sample and lab methodologies across sampling campaigns and across countries, inconsistent monitoring data and methodologies, and limitations in data coverages and data availability. A second set of challenges includes the identification of the driving forces of the potential observed changes in soil health. Observed changes can be the result of variations in natural driving factors or management practices. Moreover, it is important to disentangle changes driven by these factors from artificial factors, such as changes in monitoring methodologies. Another consideration is that most soil properties change

100 This Chapter is based on Broothaerts et al., 2026. Trends in soil health in the European Union, European Journal of Soil Sciences 77, no. 4: e70380. https://doi.org/10.1111/ejss.70380.

very slowly over time (see e.g. Fernández-Ugalde et al., 2020), indicating that monitoring efforts over multiple years or decades are needed.

In this chapter, we present changes in soil degradation indicators for which quantitative EU-wide datasets are available, which are comparable over two or more periods of time. We selected datasets collected through harmonised monitoring surveys using consistent methodologies, ensuring they are directly comparable. In this way, we can verify in a quantitative way, if these soil degradation processes are increasing or declining, and if EU soils are on track to reach healthy state by 2050. As we are focusing on multi-annual changes, we only selected datasets that span at least 9 years, in line with the comprehensive Land Use and Coverage Area Frame Survey (LUCAS) conducted by the European Commission. The selected indicators are (i) soil erosion by water, (ii) harvest erosion, (iii) soil phosphorus excess, (iv) soil phosphorus deficiency, (v) loss of soil organic carbon, (vi) soil pH, and (vii) soil sealing

6.2. Status of soil health in the EU

The current status of soil health in Europe has been well described in the 2024 report 'The State of Soils in Europe' (Arias-Navarro et al., 2024). This report provides an updated assessment compared to 2012 (Jones et al., 2012), using improved methodologies and updated datasets. The updated assessment is based on various soil degradation indicators, including nutrient excess and deficiency, soil acidification, soil carbon change, soil erosion, soil compaction, soil pollution, soil salinization and sodification, soil biodiversity change, and soil sealing and land take (Arias-Navarro et al., 2024).

In parallel, the EUSO Soil Degradation Dashboard[101] provides a spatial assessment of the state of soils in the EU. The dashboard spatially combines different EU-wide datasets to highlight the intensity and location of relevant soil degradation processes. In this way, the dashboard indicates areas in the EU that are likely to be affected by soil degradation and the specific degradation processes that affect them (Panagos et al., 2024b). The dashboard is a comprehensive and easy understandable tool on the current state of soils in the EU.

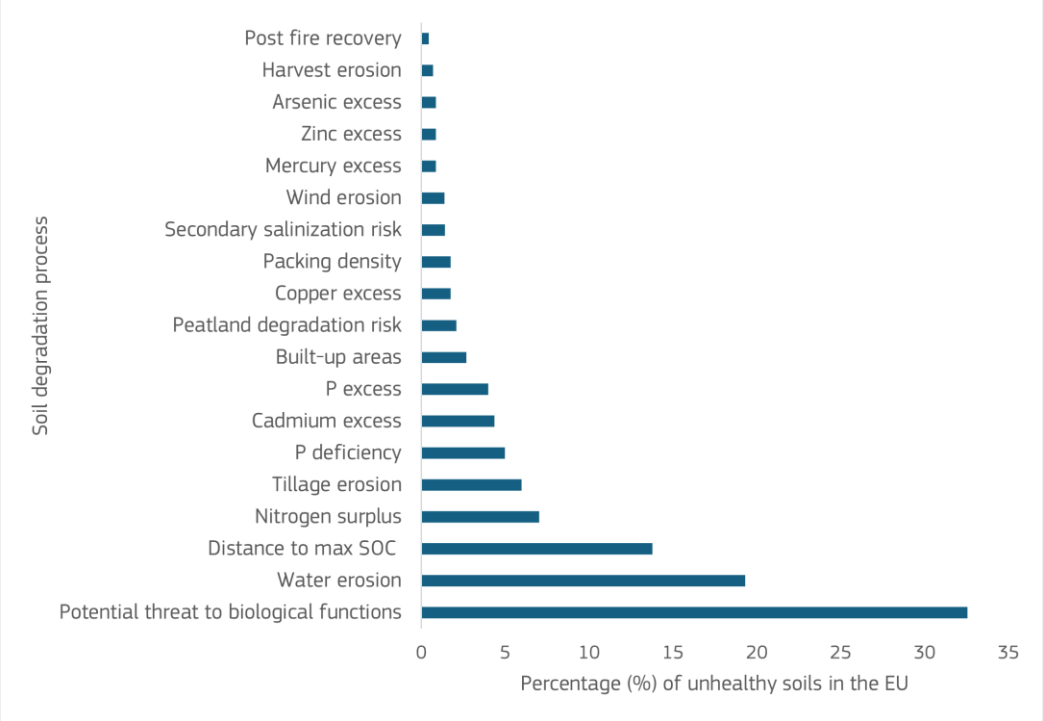
Currently, nineteen indicators representing the main soil degradation processes are included in the EUSO Soil Degradation Dashboard (**Table 13**) (Broothaerts et al., 2024; Panagos et al., 2024b). These indicators represent the state-of-the-art of soil degradation indicators, for which published EU-wide geo-spatial data are available, matching the main soil degradation processes and indicators described previously in the scientific literature (e.g. Bünemann et al., 2018; Stolte, Jannes et al., 2015). For each of these nineteen soil degradation indicators, thresholds were defined, based on scientific literature (**Table 13**). Adhering to the 'one out, all out' approach (free-from-degradation principle) it is then determined whether soils could be considered degraded or non-degraded. The current status of each soil degradation indicator is shown in **Table 13** and **Figure 19**; an extensive overview is provided in Panagos et al. (2024b) and in Broothaerts et al. (2024). The EUSO Soil Degradation Dashboard shows that approximately 62% of the EU soils are degraded (**Figure 20**). Especially concerning are agricultural and urban soils, with 89% of the agricultural soils and 88% of urban soils in the EU effected by one or more degradation processes. Also, a large proportion of grasslands (79%) and shrublands (52%) are degraded. The dashboard also shows that most soils are subject to more than one type of soil degradation. The most prevalent types of soil

[101] https://esdac.jrc.ec.europa.eu/esdacviewer/euso-dashboard/

degradation are the loss of soil biodiversity (33% of the EU), soil erosion by water (19%), and the loss of soil organic carbon (14%) (**Figure 19** and **Table 13**).

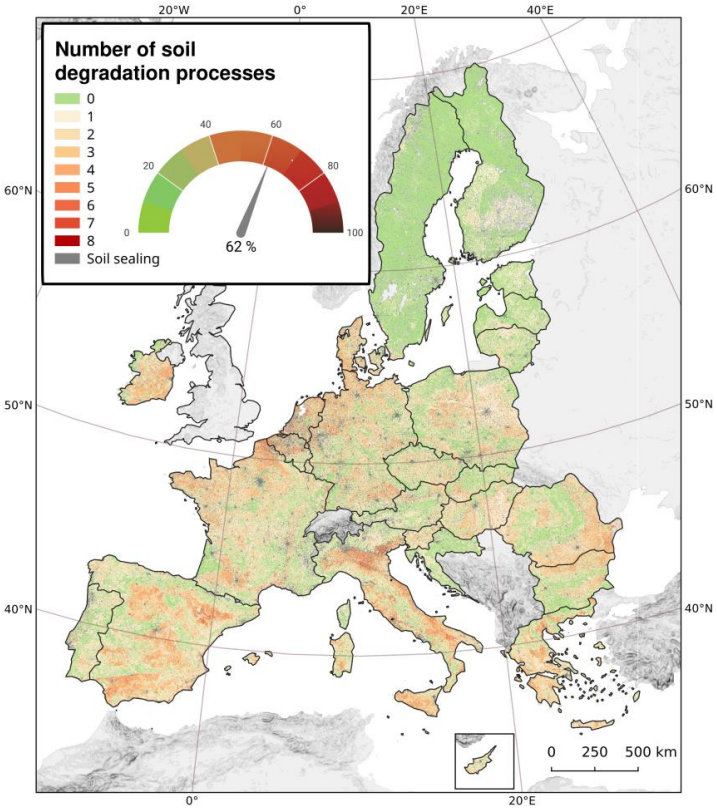
Currently, quantitative data on temporal changes are available only for seven indicators (**Table 13**). These trends are discussed in section 6.3.

Figure 19. Status of soil degradation processes, indicated as percentage (%) of unhealthy soils in the EU.



Source: Based on Panagos et al., 2024b.

Figure 20. The EUSO Soil Degradation Dashboard, showing the location of degraded soils in the EU and the number of soil degradation processes.



Source: Based on Panagos et al., 2024b.

Table 13. Soil degradation indicators included in the EUSO Soil Degradation Dashboard, their threshold to determine whether soils could be considered degraded, and their status.

Soil degradation process	**Indicator**	**Threshold**	**Status** (% of unhealthy soils)			**Trends available?**	**Reference**
			for area with data	in the EU	year of assessment		
Soil erosion	Water erosion	Erosion rate > 2 t ha^{-1} yr^{-1}	23	19	2016	yes	Panagos et al. (2020b)
	Wind erosion	Erosion rate > 2 t ha^{-1} yr^{-1}	6	1	2001-2010	no	Borrelli et al. (2017)
	Tillage erosion	Erosion rate > 2 t ha^{-1} yr^{-1}	26	6	2018	no	Borrelli et al. (2023)
	Harvest erosion	Erosion rate > 2 t ha^{-1} yr^{-1}	3	1	2000-2016	yes	Panagos et al. (2019)
	Post fire recovery	Recovery rate < 1	75	0.5	2017	no	Vieira et al. (2023)
Soil contamination	Copper excess	Cu conc > 100 mg kg^{-1}	2	2	2009	no	Ballabio et al. (2018)
	Mercury excess	Hg conc > 0.5 mg kg^{-1}	1	1	2009	no	Ballabio et al. (2021)
	Zinc excess	Zn conc > 100 mg kg^{-1}	1	1	2009	no	Van Eynde et al. (2023)
	Cadmium excess	Cd conc > 1 mg kg^{-1}	5	4	2009	no	Ballabio et al. (2024)
	Arsenic excess	P(X > 45 mg kg^{-1}) > 5%	1	1	2009	no	Fendrich et al. (2024)
Soil nutrients	N surplus	N surplus > 50 kg ha^{-1} yr^{-1}	22	7	2009	no	Grizzetti et al. (2023); Lugato et al. (2018)
	P deficiency	P deficiency < 20 mg kg^{-1}	21	8	2009	yes	Ballabio et al. (2019)
	P excess	P excess > 50 mg kg^{-1}	10	4	2009	yes	Ballabio et al. (2019)
Loss of SOC	Distance to max SOC	Distance to max SOC > 60%	53	14	2018	yes	De Rosa et al. (2024)
Loss of soil biodiversity	Potential threat to biological functions	≥ Moderately-High level of risk	37	33	2018	no	Orgiazzi et al. (2016)
Compaction	Packing density	Packing density ≥ 1.75 g cm^{-3}	2	2	2018	no	Panagos et al. (2024c)
Salinization	Secondary salinization risk	Areas in the Mediterranean where >30% has irrigation	7	1	2005	no	Siebert et al. (2013)
Loss of organic soils	Peatland degradation risk	Peatlands under hotspots of cropland	30	2	2022	no	UNEP (2022)
Soil sealing	Built-up areas	all built-up areas	2.7	2.7	2018	yes	Copernicus (2018)

Source: JRC analysis.

6.3. Temporal changes of individual soil degradation indicators over the past decades

6.3.1. Soil erosion by water

The updated version of the Revised Universal Soil Loss Equation model, RUSLE2015, which was implemented at 100-m spatial resolution, was applied consistently to quantify sheet and rill erosion for the years 2000, 2010, 2016 and 2023 across EU arable land (Borrelli and Panagos, 2026; Panagos et al., 2020b, 2015). Results show that the estimated area-weighted mean soil loss in arable lands declined substantially over the study period, from 3.35 t ha^{-1} yr^{-1} in 2000 to 2.67 t ha^{-1} yr^{-1} in 2010, before remaining stable in 2016 (2.67 t ha^{-1} yr^{-1}), and decreasing further to 2.38 t ha^{-1} yr^{-1} in 2023. Overall, this represents a reduction of ca 30% between 2000 and 2023 in arable lands, characterised by a pronounced decline in the first decade (−20.1% from 2000 to 2010), a period of relative unchanged between 2010 and 2016, and a renewed decrease of −12.2% between 2016 and 2023. Mean soil loss decreased over the 2000–2023 period across all EU MS.

Across all EU erodible lands, including arable land, grasslands, forests, and other relevant land uses, mean soil loss by water erosion shows a comparable declining trend (-13.8%) over the 2000-2023 period. Average erosion rates decreased from 2.71 t ha^{-1} yr^{-1} in 2000 to 2.45 t ha^{-1} yr^{-1} in 2010, indicating a substantial reduction in the first decade. This improvement then stabilised, with nearly unchanged values in 2016 (2.46 t ha^{-1} yr^{-1}), before declining further to 2.38 t ha^{-1} yr^{-1} in 2023 (**Table 14**).

In the EUSO Soil Degradation Dashboard, soils with a soil loss above 2 t ha^{-1} yr^{-1} are considered degraded, as they experience unsustainable soil erosion rates. The area affected by soil loss above this threshold has decreased markedly across the EU over the past two decades (**Table 14** and **Figure 21**). In 2000, ca 27% of the EU erodible land, exceeded this threshold (i.e. 23% of all EU land). This share declined to 24.4% (21% of EU land) in 2010 and remained unchanged in 2016 before declining again by 2023 to 23.3% (20% of EU land). At the MS level, nearly all countries show decreases in the extent of arable land experiencing unsustainable erosion, with the largest improvements observed in France, Spain, Italy, Poland and Germany. Overall, the aggregated evaluation of soil erosion by water at the EU-level shows that this indicator is on track and progressing to reach the target of healthy soils by 2050 (Borrelli and Panagos, 2026; European Commission, 2025b; Panagos et al., 2020b, 2015).

Because all RUSLE2015 modelling parameters were kept constant across the four benchmark years, with the exception of the C-factor (Borrelli and Panagos, 2026, 2020; Panagos et al., 2015), the temporal evolution of soil loss can be directly attributed to changes in land management and land cover. The marked reductions in mean soil loss, particularly between 2000 and 2010 and again after 2016, mirror a substantial decline in the C-factor at EU scale. This reflects revegetation after land abandonment (Brandolini et al., 2023; García-Ruiz and Lana-Renault, 2011) and the substantial expansion of conservation-oriented practices across Europe between 2000 and 2023, such as conservation tillage, no-till adoption, cover crops and plant-residue retention (Borrelli and Panagos, 2026, 2020; Panagos et al., 2015). The timing and magnitude of these improvements correspond closely with the gradual greening of the CAP and the GAEC requirements, as well as the implementation of both mandatory and voluntary soil-related standards (European Commission, 2025b). Although the modelling framework does not isolate the influence of individual measures, the results suggest that EU soil and agricultural policies have played a relevant role in enhancing erosion mitigation throughout the EU and have helped counteract part of the increasing erosive

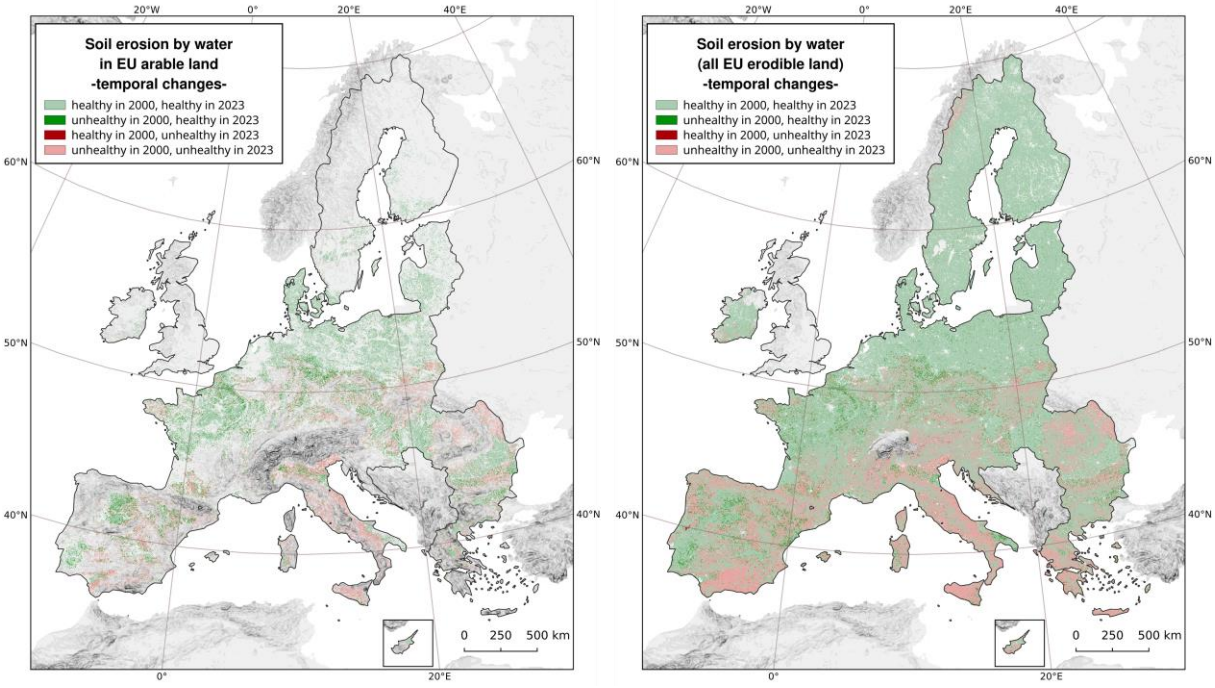
pressure associated with climatic intensification (European Commission, 2025b). Detailed analysis of CAP Strategic Plans over the 2023-2027 period suggests that the application of GAEC standards can further decrease soil erosion by water by 5.4% in agricultural lands of 13 EU MS (European Commission, 2025b). However, important criticalities remain, as persistent soil erosion hotspots, uneven adoption of conservation practices and increasing climate pressures, particularly in vulnerable systems such as Mediterranean perennial crops (Borrelli et al., 2025).

Table 14. Mean soil loss due to water erosion and changes in mean soil loss for EU arable land and all EU erodible land, for the period 2000-2023.

Year		**2000**	**2010**	**2016**	**2023**
EU arable land	Mean soil loss due to water erosion (t ha^{-1} yr^{-1})	3.4	2.7	2.7	2.4
	Changes in mean soil loss (%)	-	-20.1	-0.1	-12.2
	Area above 2 t ha^{-1} yr^{-1} (%)	41.0	33.8	33.6	29.5
All EU erodible land	Mean soil loss due to water erosion (t ha^{-1} yr^{-1})	2.7	2.5	2.5	2.4
	Changes in mean soil loss (%)	-	-9.6	-0.1	-3.5
	Area above 2 t ha^{-1} yr^{-1} (%)	27	24.4	24.4	23.3

Data source: Panagos et al. (2020b) and Borrelli and Panagos (2026).

Figure 21. Temporal changes in soil degradation due to water erosion (above threshold of 2 t ha^{-1} yr^{-1}) in the period 2000-2023, for (left) EU arable land and (right) all EU erodible land.



Data source: Panagos et al. (2020b) and Borrelli and Panagos (2026).

6.3.2. Harvest erosion

During the harvest of root and tuber crops, such as sugar beets and potatoes, soil particles often stick to the crop and ends up being transported from the field. This phenomenon is referred to as soil loss by crop harvesting or harvest erosion (Ruysschaert et al., 2004). Field observations and measurements have shown that significant amounts of soil can be removed from the field due to this process (Kuhwald et al., 2022; Panagos et al., 2019).

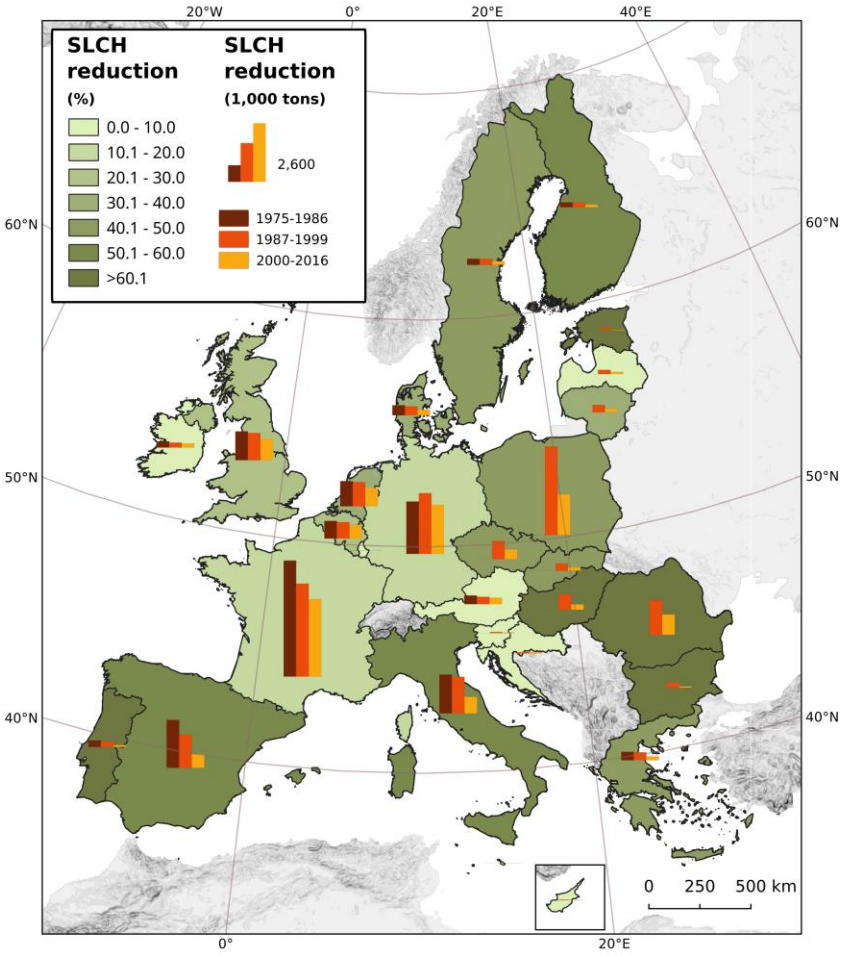
Based on crop statistics of the European Commission Statistical Office (Eurostat, 2017) aggregated at regional and national level and soil texture data from LUCAS Soil, Panagos et al. (2019) estimated harvest erosion in the EU for three periods (1975–86, 1987–99 and 2000–2016). Results of Panagos et al. (2019) show that during the period 1987-1999, harvest erosion associated with sugar beets and potatoes in the EU was around 23.4 million t yr^{-1}. During the subsequent period 2000–2016, this soil loss is estimated to be significantly lower, at 14.7 million t yr^{-1}. This is a decrease in soil loss due to harvest erosion in the EU by 37.2%. The decreasing trend is observed in all EU MS. The highest absolute decrease is found in Poland followed by Italy, Spain and France (**Figure 22**). Data from EU-15 MS from 1975-1986 confirms this long-term decreasing trend (Panagos et al., 2019) (**Figure 22**).

The observed decrease in harvest erosion in the EU is mainly due to the decrease in the extent of root crop cultivation in the past decades (Eurostat, 2025; Kowalska and Gurkowa, 2019). In addition, technological developments in machinery harvesting, increasing farmers' awareness and the raising of sustainability concerns in the sugar beet industry have positively contributed to the decrease in harvest erosion (Panagos et al., 2019).

During the most recent period (2000-2016), harvest erosion was around 0.13 t ha^{-1} $year^{-1}$ (Panagos et al., 2019). In the EUSO Soil Degradation Dashboard, soils with a soil loss by harvest erosion above the unsustainable erosion rate of 2 t ha^{-1} yr^{-1} are considered degraded (**Table 13**). The area affected by soil loss due to harvest erosion above this threshold has decreased markedly across the EU over the past two decades. During the period 2000-2016, 3% of the EU arable land exceeded this threshold (i.e. 0.7% of the EU land). For the period 1987-1999, this is estimated at ca 4% (0.9% of the EU land). This shows that harvest erosion is decreasing and progressing in the right direction to reach the target of healthy soils in the entire EU.

However, it should be noted that harvest erosion only plays a minor role in total erosion rates. The soil loss by harvest erosion (0.13 t ha^{-1} $year^{-1}$) is much lower than the mean soil loss due to water erosion (estimated at 2.4 t ha^{-1} yr^{-1}, see section 6.3.1), tillage erosion (estimated at ca 3.3 t ha^{-1} yr^{-1}, see Van Oost et al. (2009)) and wind erosion (estimated at ca 0.53 t ha^{-1} yr^{-1}, see Borrelli et al. (2017)). However, harvest erosion is an unevenly distributed process that locally may assume a different relevance. For instance, in countries with a dominating fraction of root and tuber crops grown in their arable land, harvest erosion can be a major concern. For instance, in the Netherlands, harvest erosion may increase the overall soil loss rate in arable lands by 1.13 t ha^{-1} $year^{-1}$, in Belgium by 0.91 t ha^{-1} $year^{-1}$ and in Ireland by 0.54 t ha^{-1} $year^{-1}$ (Panagos et al., 2019), and thus bringing soil losses closer to unsustainable rates of 2 t ha^{-1} yr^{-1}.

Figure 22. Decrease (%) of harvest erosion during the periods 1975–1986, 1987–1999 and 2000–2016.



Source: Panagos et al., 2019.

6.3.3. Soil phosphorus content

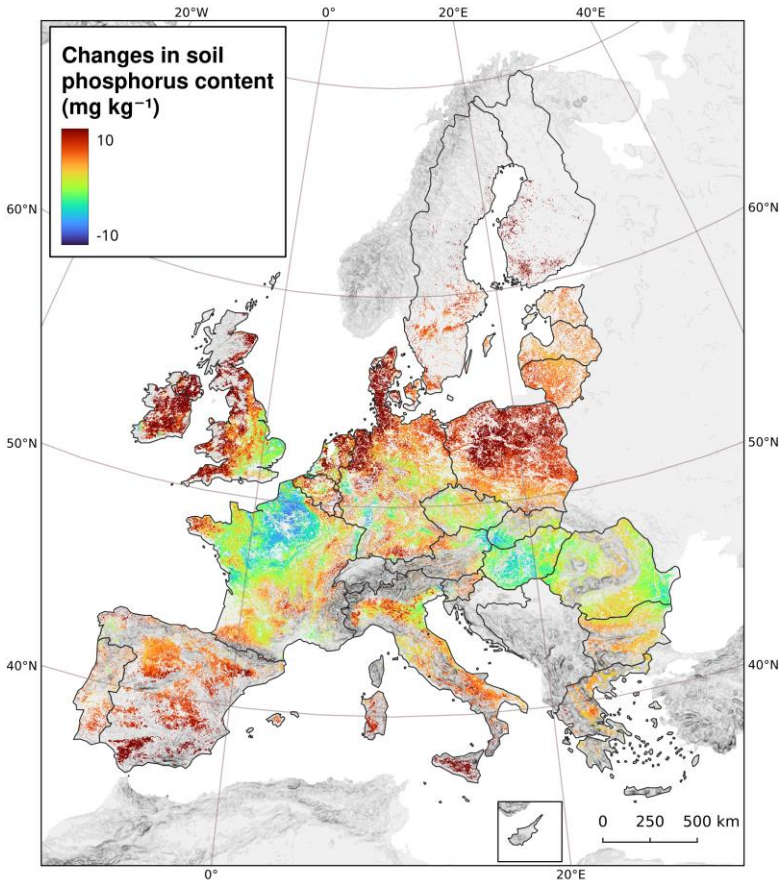
Phosphorus (P) is an essential nutrient for plant growth, and its application has increased in the EU since the 1960s, reaching a peak in the 1980s (Sattari et al., 2012). However, the excessive application of phosphorus has resulted in high soil phosphorus stocks in some EU agricultural soils, which can negatively affect soil functioning and water quality (Ceulemans et al., 2014; Mekonnen and Hoekstra, 2018; Sandström et al., 2023; Vigiak et al., 2023). In a recent study, Van Eynde et al. (under review) assessed if and where soil P has changed in EU agricultural land from 2009 to 2018. The LUCAS soil survey data from 2009 (P_{2009}) and 2018 (P_{2018}) were used to assess the changes in soil phosphorus content in EU agricultural land over the period 2009-2018. To avoid the interference of statistical artefacts due to mathematical coupling and regression to the mean on the conclusions, they opted not to model the change in soil P directly as done previously when assessing changes in soil properties. Instead, they modelled the joint behaviour of P_{2009} and P_{2018} with a bivariate distribution using GAMLSS-Copula, which combines the marginal distributions from Generalized Additive Models for Location, Scale and Shape (GAMLSS, Stasinopoulos et al., 2018) with the copulas described by Joe (2014), a method previously referred to as a bivariate copula additive model for location, scale and shape (Marra and Radice, 2017).

The results of Van Eynde et al. (under review) show that soil phosphorus is mostly increasing in EU27+UK agricultural land, with an average increase of 4 mg kg^{-1} (i.e., 12.2% of the initial average)

in nine years (**Figure 23**). Soil phosphorous is mostly increasing in areas of northern and southern Europe, Ireland and the western parts of the UK. A smaller increase or a decrease is observed in some parts of France, the UK, Slovakia, Hungary and Bulgaria (**Figure 23**). The increase is mostly pronounced in soils with low (< 20 mg kg^{-1}) and very high (> 50 mg kg^{-1}) soil P concentrations in 2009. In the EUSO Soil Degradation Dashboard, agricultural soils with a phosphorus content above 50 mg kg^{-1} (P excess) and agricultural soils with a phosphorus content below 20 mg kg^{-1} (P deficiency) are considered degraded. The results of Van Eynde et al. (under review) show that the probability of observing phosphorus excess in agricultural soils (i.e. > 50 mg kg^{-1}) increased between 2009 and 2018 across large parts of the EU. As a result, the percentage of degraded soils in the entire EU regarding P excess increased from 2.3% to 3.9% (**Figure 24**), while the analysis was only done for agricultural soils. This shows that P excess is increasing and not evolving in the right direction to reach the target of healthy soils in the entire EU. On the other hand, the probability of observing phosphorus deficiency (i.e. < 20 mg kg^{-1}), is decreasing between 2009 and 2018. As a result, the percentage of degraded soils in the entire EU regarding P deficiency decreased from 11.2% to 4.9% (**Figure 24**).

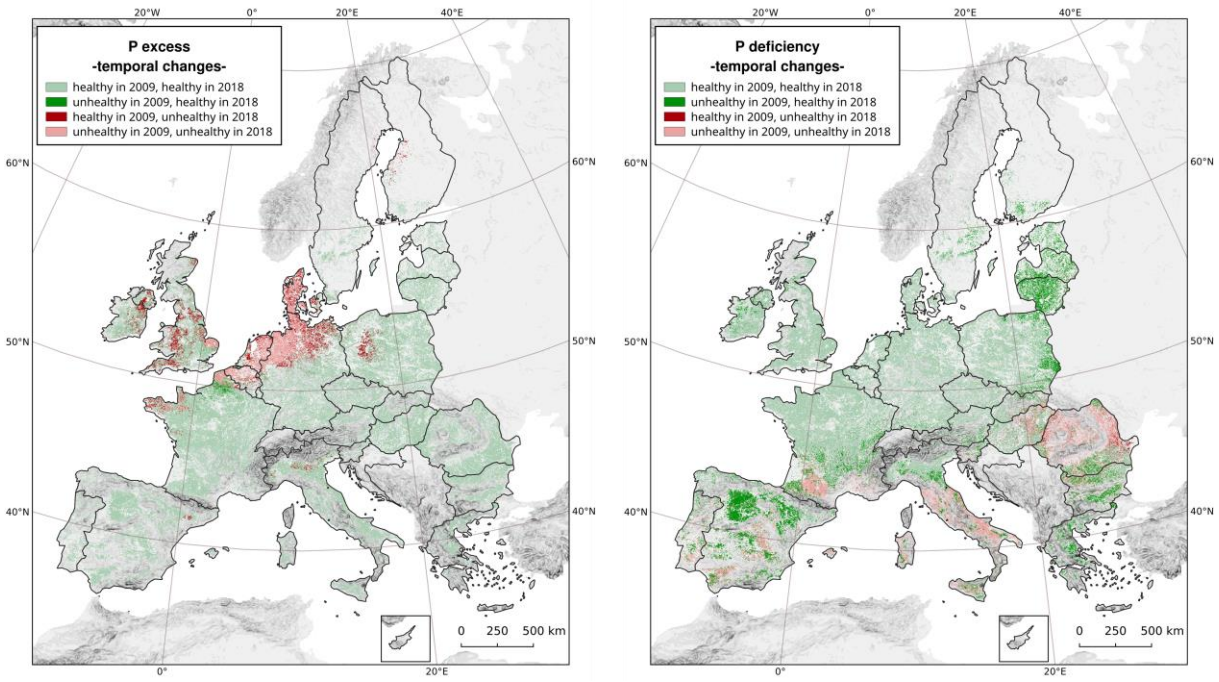
The modelling approach of Van Eynde et al. (under review) also show that phosphorus inputs (i.e. sum of mineral and organic fertilizers) are the most important variable explaining the increase or decrease in soil phosphorus at EU scale. The change in soil P becomes positive when P inputs are above 15 kg ha^{-1} $year^{-1}$.

Figure 23: Change in soil phosphorus content in EU27+UK (in mg kg^{-1}) over the period 2009-2018. Results are based on median model predictions for P_{2009} and P_{2018}.



Data source: Van Eynde et al., under review.

Figure 24. Temporal changes in the period 2009-2018, for (left) soil degradation due to phosphorus excess (P>50 mg kg^{-1}), and (right) phosphorus deficiency (P<20 mg kg^{-1}).



Data source: Van Eynde et al., under review.

6.3.4. Loss of soil organic carbon

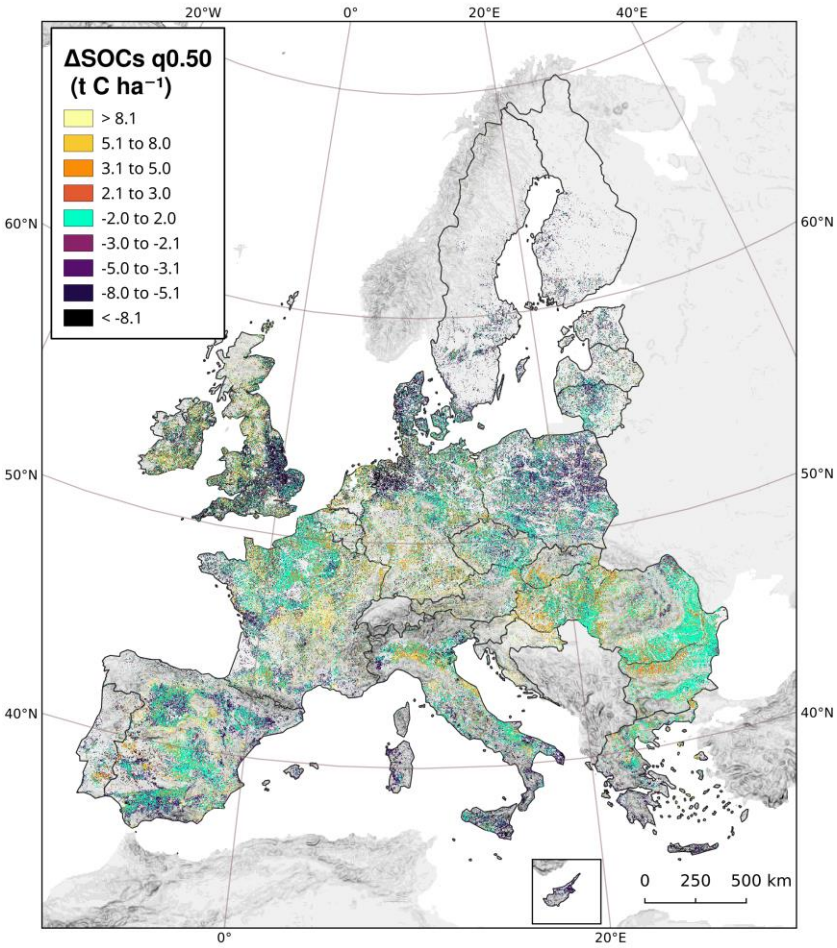
Soil organic carbon (SOC) dynamics were assessed based on the soil measurements from LUCAS Soil in 2009 and 2018 for all mineral agricultural soils across the EU and the UK (De Rosa et al., 2024). Results show widespread yet spatially differentiated trends. Total SOC losses from croplands were moderate in relative terms totalling 0.75% of initial stocks. This corresponds to 70 Mt C lost from an estimated 9.3 Gt C stored in the top 20 cm during the period 2009-2018 (De Rosa et al., 2024). These results show that soil organic carbon stocks are decreasing and trending in the opposite direction in relation to the target of healthy soils in the EU.

When expressed per unit area, the median SOC change for the EU and the UK was –0.4 t C ha^{-1} (in the top 20 cm) over the decade, though national and regional patterns diverge substantially (**Figure 25**). Some MS, such as Austria and Slovenia, recorded increases reaching 3 t C ha^{-1} between 2009 and 2018. Conversely, the largest SOC losses (up to –4.9 t C ha^{-1}) were observed in northern Europe, where soils typically have lower clay contents and therefore a reduced capacity to physically protect organic matter. Despite high initial SOC stocks, these soils are more vulnerable to carbon losses (Breure et al., 2025). However, these patterns are derived from repeated measurements of the LUCAS soil survey (2009 and 2018) and therefore represent spatially consistent, but not exhaustive, estimates of SOC change, subject to the survey's sampling design and associated uncertainties. While these estimates broadly align with observations from several national soil monitoring networks (Heikkinen et al., 2022) important exceptions remain (Bellamy et al., 2005; Froger et al., 2024; Knotters et al., 2022; Poeplau and Don, 2015). Much of central Europe displayed near-stable SOC levels across the period. In the Mediterranean, characterised by higher temperatures, lower rainfall and lower initial SOC stocks, SOC changes ranged widely from –5 to +1.5 t C ha^{-1}. Although Mediterranean soils are generally carbon-poor, the study of Breure et al. (2025) suggests a lower

vulnerability of the remaining SOC pool and a potential for long-term carbon accrual under improved management practices.

Changes in land use and agricultural management are considered the dominant drivers of SOC dynamics over the short- to medium-term. A well-documented example is the conversion of grasslands to croplands, which is commonly associated with SOC declines of approximately 36% over a 20-year period (Poeplau et al., 2011). Limiting such conversions could therefore contribute substantially to climate mitigation by safeguarding existing soil carbon stocks (De Rosa et al., 2024). At the same time, decisions to convert grasslands are frequently linked to food security demands, giving rise to trade-offs between maintaining soil carbon and maximising food production efficiency. Next to land use changes, climate change has an impact on SOC dynamics, as soils release more carbon into the atmosphere under warmer climate conditions and heavy rainfall events can lead to spatial redistribution of SOC through soil erosion (Lugato, 2024; Wang et al., 2024).

Figure 25. Median change in soil organic carbon (SOC) content at 0–20 cm soil depth, in the period 2009–2018.



Data source: De Rosa et al., 2024.

6.3.5. Soil pH

Soil pH differs across the EU (Ballabio et al., 2019), reflecting climatic conditions, parent material, vegetation and past management practices such as liming (Ballabio et al., 2019). In terms of soil

acidity, soils with a very low pH (pH < 5.5) are present in 10% on the agricultural land across Europe (Arias-Navarro et al., 2024).

Soil acidification occurs when the acid neutralising capacity of the soil is reduced, which leads to a decrease in pH. Soil acidification is defined as a reducing pH value over time along pH interval. Methodology for the assessment of trends in changing pH value over time should be provided based on soil reactivity as proposed by Kabala et al. (2025) on the relationship between base saturation and soil pH. Other factors affecting soil pH and spatial patterns of soil pH across Europe have been recently identified (Lebron et al., 2025). They found that human activities, such as food production and associated land management, are displacing soils from their natural equilibrium, particularly towards the pH range of 6–7. These results suggest that European soils have undergone partial leaching, contributing to a trend of acidification.

To accurately assess changes in soil pH over time, Yunta et al. (under review) employed a comprehensive methodology, considering both actual and available acidity defining soil reactivity. The soil pH indicator is then calculated as the ratio of soil pH variations over time to soil reactivity, providing a normalized measure of pH change (Equation 1).

$$\text{Equation 1:} \qquad pH_{Ind_w_{\mathrm{yx}}} = \frac{\Delta pH_{\mathrm{yx}_w}}{\frac{\left|\Delta pH_{WCa_y}\right| + \left|\Delta pH_{WCa_x}\right|}{2}}$$

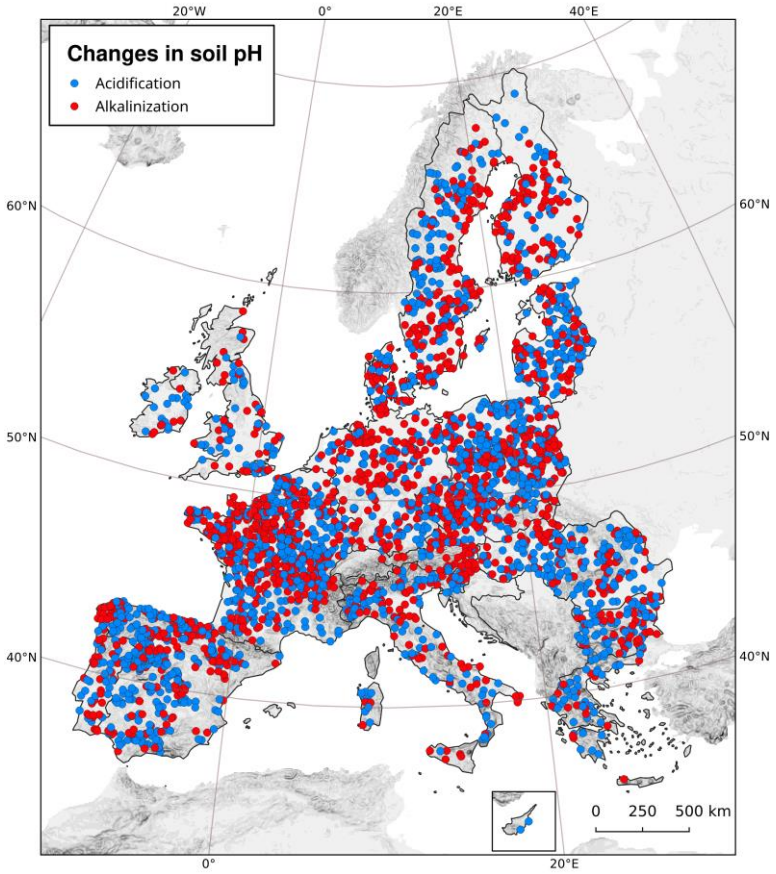
In equation 1, $pH_{Ind_w_{\mathrm{yx}}}$ stands for the soil pH indicator for actual acidity and it is determined by dividing the variations in soil pH measurements ($\Delta pH_{\mathrm{yx}_w}$) between years *y* (2018) and *x* (2009) by the soil pH buffering capacity ($\frac{\left|\Delta pH_{WCa_y}\right|+\left|\Delta pH_{WCa_x}\right|}{2}$) calculated as the absolute values of the changes in soil pH between water and calcium chloride measurements for each of years *y* and *x*.

Yunta et al. (under review) used this soil pH indicator to identify trends in soil acidification (values below -1) and alkalinisation (values above +1). The pH indicator was calculated for each of the 13326 revisited points from LUCAS Soil Survey 2009 and 2018.

Results indicate no significant changes between 2009 and 2018 in soil pH in three quarter (74%) of the revisited LUCAS Soil points. For the remaining quarter, half of the points are affected by acidification (14% of the revisited LUCAS Soil points) while the other half is affected by alkalinisation (12% of the revisited LUCAS Soil points) (**Figure 26**). The trends are comparable over the different land use types, while a light dominance of acidification is noticed in woodlands and grasslands (**Table 15**). These trends align with the findings of Blake et al. (1999) showing that acid deposition resulted in severe acidification of woodlands and grasslands throughout the twentieth century and that the more recent decline in acid deposition have not reversed this process.

Overall, the methodology for assessing soil pH trends developed by Yunta et al. (under review) provides a valuable tool for monitoring and understanding soil pH changes and can be used to compare repeated soil surveys. For the period 2009 – 2018, no clear trends were found.

Figure 26. Soil pH changes between 2009 and 2018, for the revisited LUCAS Soil 2009 and 2018 points. Points with no significant changes are not displayed.



Data source: Yunta et al., under review.

Table 15. Soil pH changes between 2009 and 2018 across different land cover classes, for the revisited LUCAS Soil 2009 and 2018 points.

Land cover classes	**N**	**Acidification**	**No effect**	**Alkalinisation**
Cropland	5902	13%	74%	14%
Woodland	3891	13%	78%	9%
Grassland	2692	17%	68%	14%
Bare land	454	15%	73%	11%
Shrubland	312	16%	72%	12%
Artificial land	51	18%	67%	16%
Wetlands	24	17%	75%	8%
Total	**13326**	**14%**	**74%**	**12%**

Data source: Yunta et al., under review.

6.3.6. Soil Sealing

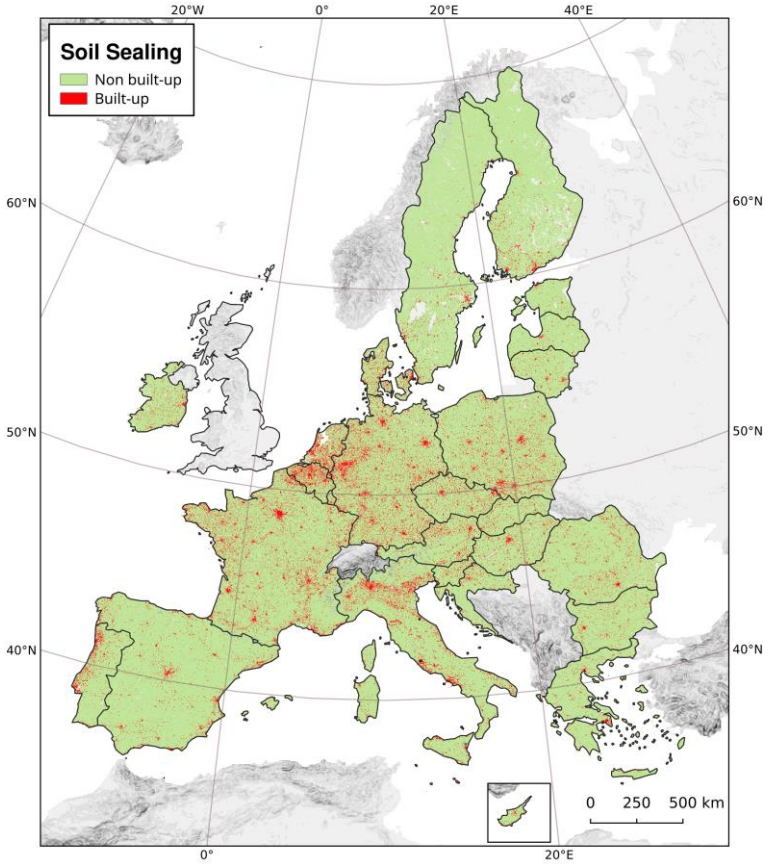
Soil sealing is the permanent covering of soils with an impermeable artificial material, such as buildings, constructions and roads. Soil sealing leads to a loss of soil functions and ecosystem services, such as a decrease in water infiltration and gas exchange and loss in biodiversity (see e.g. Ferreira et al., 2018; Scalenghe and Marsan, 2009), and is one of the main soil degradation processes. The European Commission introduced a 'no net land take by 2050' initiative in its roadmap to a resource efficient Europe, aiming to ensure that all new build-up areas are on brownfields or that any new land take is compensated (European Commission, 2011). Reaching no net land take by 2050 is also included in the long-term objectives of the EU Soil Strategy for 2030 (European Commission, 2021a), the EU Biodiversity Strategy for 2030 (European Commission, 2020) and the Mission Soil (European Commission, 2021b).

Soil sealing at the EU-scale is estimated by using the high-resolution Copernicus imperviousness datasets of the European Environmental Agency (EEA), available for the period 2006 to 2018 (3-yearly) at 20m and 100m resolution (**Figure 27**). Imperviousness considers soils covered by non-permeable materials and is used as an indicator for soil sealing. Data show that in 2018, 110 702 km^2 of soil was sealed in the EU, which is 2.7% of the total land area of the EU (**Figure 28**) (European Environmental Agency, 2024). Twelve years earlier, in 2006, 107 097 km^2 of soil was sealed (i.e. 2.6% of the total land area of the EU). The increase in sealed area between 2006 and 2018 was 3606 km2, which is an increase of 3.4% at the level of the EU (**Figure 28**). The largest increase in sealed surface at the EU-level was in the period 2006-2009 (increase of 1088 km^2 or 1%) and 2009-2012 (increase of 1156 km^2 or 1.1%). The increase in sealed surface was slightly lower in the next period (2012-2015, 567 km^2 or 0.5%) but increased again in the period 2015-2018 (794 km^2 or 0.7%) (**Table 16**) (European Environmental Agency, 2024). First results for year 2021 show again a larger increase in the period 2018-2021 (1622 km^2 or 1.4%) (European Environmental Agency, 2025). These data show that the EU is not yet close to the no net land take target.

Among the MS, the increase in soil sealing between 2006 and 2018 was the largest in Cyprus (11% increase compared to 2006), Poland (5.4% increase) and Spain (4.9% increase). The sealing level is the highest in Malta (17% of the total area), Netherlands (10.3%) and Belgium (9.2%) (**Figure 28**) (European Environmental Agency, 2024).

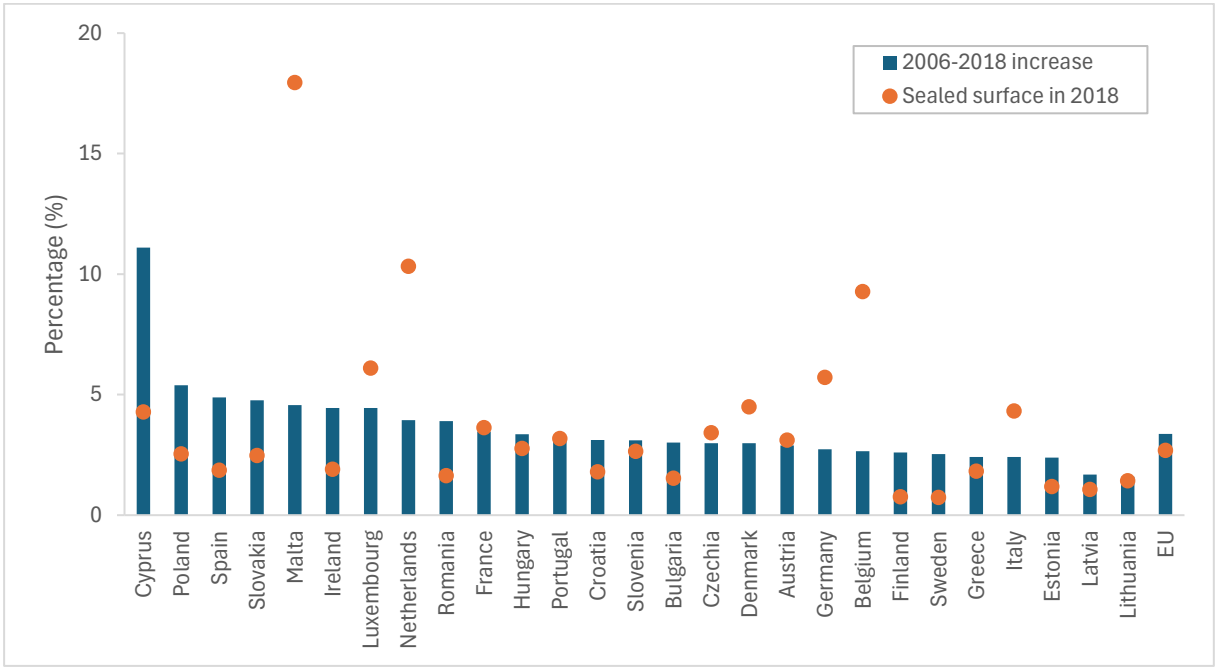
The driving factors for the increase in sealed area are linked to population growth and urbanisation and the associated needs for more housing and new infrastructure. Also, economic development and the associated need for more industrial and commercial buildings and transport infrastructure causes new sealed areas (Arias-Navarro et al., 2024; Naumann et al., 2019).

Figure 27. Soil Sealing in 2018.



Data source: European Environmental Agency, 2024.

Figure 28. Soil sealing in 2018 (in percentage of the total area) and increase in soil sealing in the period 2006-2018 (rate of change between 2006 and 2018).



Data source: European Environmental Agency, 2024.

Table 16. Soil sealing and increase in soil sealing in the EU between 2006 and 2021.

	2006	2009	2012	2015	2018	2021
soil sealing in the EU (km2)	107097	108185	109341	109908	110702	112324
increase in soil sealing (km2)	-	1088	1156	567	794	1622
increase in soil sealing (%)	-	1.0	1.1	0.5	0.7	1.4

Data source: European Environmental Agency, 2024.

6.4. Outlook: Future changes of individual soil degradation indicators

6.4.1. Soil erosion by water

Soil erosion due to water is projected to increase by 13-22.5% in the EU and UK by 2050 (Panagos et al., 2021). This increase is mainly due to an increase of rainfall intensity by 15.7-25.5% by 2050 (Panagos et al., 2022c). The increase in soil loss is expected to be most pronounced in central and northern Europe, where losses are expected to double across some areas. In contrast, soil erosion in the Mediterranean basin is projected to increase only slightly due to a reduced precipitation depth alongside increased rainfall intensity (Donnelly et al., 2017; Panagos et al., 2021). Projected land use changes in the EU and UK, indicating an overall increase in pasture coverage at the expense of croplands, will not be able to compensate this increase. The projected shift in land use is expected to mitigate the high erosion increases by only 3%. Thus, although this indicator was on track and erosion rates decreased in the period 2000-2023 (see section 6.3.1), trends are predicted to reverse in the coming decades, and this indicator will likely not meet the target of healthy soils in 2050 (**Table 17**).

Agro-environmental policies are the primary mechanism for mitigating the future negative trend of soil erosion by water in the EU. The implementation of soil conservation measures, such as cover crops and reduced tillage, should cover at least 50% of the hotspots (i.e., areas where soil losses exceed 5 t ha-1 yr-1) to neutralize the potential future impact of climate change on water erosion (Panagos et al., 2021).

6.4.2. Harvest erosion

The area of root crop cultivation (e.g. sugar beets and potatoes) in the EU is expected to further decrease in the next decade. For instance, the area of sugar beets cultivation is expected to decrease by 25% by 2035 (European Commission, 2024). This will lead to a further decrease in the soil losses due to harvest erosion by 2035. Also, further technological developments in machinery harvesting as well as increasing awareness of farmers and the sugar beet industries are expected to contribute to the continued decrease of harvest erosion in the EU in the upcoming decades. Quantitative estimates of these processes expected decrease are however not available. Overall, this indicator is likely progressing towards the target of healthy soils by 2050 (**Table 17**).

6.4.3. Soil phosphorus content

As shown in section 6.3.3, phosphorus inputs (i.e. sum of mineral fertilizers and organic inputs) are the most important drivers of soil P changes between 2009 and 2018 (Van Eynde et al., under review). If management practices remain unchanged, a further increase in soil P content in the upcoming years is expected. Which will as a consequence lead to a further increase in EU soils affected by P excess (off track to meet the target of healthy soils in 2050) and a further decrease

in P deficiency in EU soils (on track to meet the target of healthy soils in 2050) (**Table 17**). Unlike for nitrogen, there are currently no EU policies that set direct limits on phosphorus application rates; only indirectly. The CAP is currently the only EU tool in supporting the sustainable use of phosphorus inputs, for instance through the Farm Sustainability Tool for Nutrients. In the coming years, also the Soil Monitoring and Resilience Directive may highlight issues with current phosphorus application rates in the context of current soil P content and changes after multiple monitoring cycles. Soils with high P levels should be supported to change their management strategies to reach a healthy status and to protect and improve environmental soil and water quality in the EU.

6.4.4. Soil organic carbon losses

Despite some environmental actions to protect soils introduced with the CAP reform in 2013, climate change (in particular warming) seems to accelerate SOC decomposition. A long-term projection study using LUCAS data and SOC size fractionation into particulate (POM) and mineral-associated organic matter (MAOM), estimated SOC losses up to 2.5 ± 1.2 PgC by 2080 in a high warming scenario (RCP8.5) (Lugato et al., 2021). And thus, this indicator will likely be off track to meet the target of healthy soils in 2050 under changing temperature and rainfall patterns under a high warming scenario (**Table 17**). Grasslands were shown to be less sensitive to climate change, while forests projected to lose 20% and 6% of their initial POM and MAOM pools, respectively. A new study, also based on LUCAS, suggests that SOC in agricultural soils are classified as at high risk in between 43 and 83 Mha (Breure et al., 2025). Current data and different projections strongly indicate the need to protect and largely deploy new measures to protect or accrue SOC across all ecosystems.

6.4.5. Soil sealing

Projections indicate a likely net-expansion of built-up areas in the coming years (Perpiña et al., 2019) and it is uncertain that the rate of expansion will slow down (**Table 17**) (European Environmental Agency, 2025). Built-up areas are projected to expand mainly in and around major cities, with an increase in urban residential areas and areas for economic activities. Also, touristic hotspots and heavily industrialised zones are expected to experience a further increase in build-up and sealed areas. Most additional land take will occur in agricultural land. However, large inter-regional differences are expected, with a decline in built-up areas in some remote parts of the EU (Perpiña et al., 2019, 2018).

The EU Soil Strategy for 2030, the EU Biodiversity Strategy for 2030 and the Mission Soil have the long-term objective of no net land take by 2050. As shown in section 6.3.6, the EU is currently behind in making the no net land take target. There needs to be an efficient implementation of the relevant EU Strategies at national and regional level and significant reductions in the net land take over the years to come. To meet the no net land take objective by 2050, the EU would need to reduce its net land take by ca 27 km^2 annually assuming a linear evolution (European Environmental Agency, 2025).

6.5. Discussion

Over the past decades, clear progress was made regarding soil monitoring at the EU level (see Chapter 4 and **Figure 29**). The launch of LUCAS Soil in 2009 was a major milestone in EU-wide soil monitoring and is still the best available tool to detect trends in soil properties and soil degradation indicators at the EU scale. In 2021, with the launch of the EU Soil Strategy, the Mission Soil and the

EUSO, new data, tools and frameworks became available for EU-wide soil monitoring. The publication of the EUSO Soil Degradation Dashboard in 2023 was another important milestone, providing for the first time a spatial assessment of unhealthy soils in the EU and the degradation processes affecting them. These monitoring efforts made available datasets for trend analysis. In this chapter, trends were described for seven soil degradation indicators, based on quantitative, EU-wide datasets collected by harmonised monitoring surveys.

The EU Soil Strategy for 2030, the Mission Soil, and the SMRD, three important policy initiatives for soil protection in the EU, include the aspirational objective of healthy soils by 2050, adhering to the free-from-degradation principle. The trends described in this manuscript show that in the past decades three soil degradation indicators were evolving in the right direction to reach this objective (i.e. soil erosion by water, harvest erosion and phosphorus deficiency, see section 6.3). The main drivers for these trends are the gradual greening of the CAP (soil erosion), technical developments and decrease in the area of root crop cultivation (harvest erosion) and agricultural management practices (phosphorous deficiency). The three other soil degradation indicators (i.e. phosphorous excess, loss of soil organic carbon and soil sealing, see section 6.3), however, deteriorated, being off track to reach the targets (**Table 17**). Drivers for these trends include land use changes, climate changes and agricultural management practices (loss of soil organic carbon), agricultural management practices (phosphorous excess) and population growth and urbanisation (soil sealing).

Evaluating the effectiveness of the EU Soil Strategy and the Mission Soil in protecting and restoring soils was not yet possible based on the available data. The trends presented cover only partly the period since the start of the Mission Soil and the publication of the EU Soil Strategy, both in 2021 (see **Table 17**). Moreover, these trends cover a limited time frame (four indicators cover 9 years, see **Table 17**) whereas measuring periods covering multiple decades are needed to detect clear effects of soil policies, as most soil properties change very slowly over time. Thus, more data after the start of these policy initiatives and longer measuring periods are needed to be able to evaluate the effectiveness of these policy initiatives. For this, the results of the LUCAS Soil survey in 2022 (available early 2027) and the planned survey in 2027 (results available ca. two years after) will be highly important and will allow an extended trend analysis. Also data from Mission Soil projects and the monitoring framework put in place by the SMRD (data available from 2031 onwards) will be crucial.

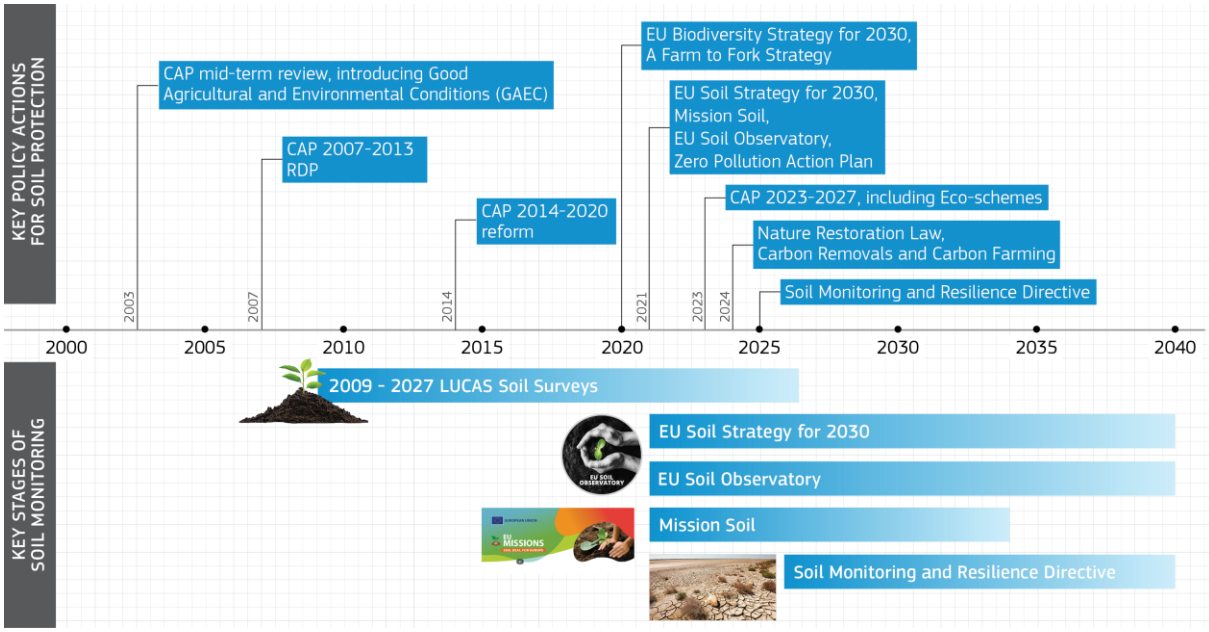
The trend analysis of the seven indicators presented in this study provides a first quantitative assessment of trends in soil health in the EU over the past years or decades. It is also lacking an optimal level of harmonisation regarding methodology and spatial and temporal coverage. Moreover, next to the seven soil degradation indicators presented in this paper, there are still 13 soil degradation indicators in the EUSO soil degradation dashboard for which quantitative trends are not yet available (see **Table 13**). Even more, not all soil degradation processes are included in the EUSO dashboard. For instance, indicators, thresholds and trends are still missing for peatland degradation, source pollution, diffuse pollution and emerging pollutants, reduced water-holding capacity, gully erosion, and others. The EUSO aims to complete the assessment of the state of soil health in the EU as well as the trend analysis in the future and aims to harmonise the methodology for the trend analysis and the spatial and temporal coverage of the indicators. New scientific data from Mission Soil research projects and collaboration between the EUSO and these Mission Soil projects will be important to complete this assessment. Indeed, thanks to the R&I projects and the Living Labs of the Mission Soil (e.g. The Mission Soil projects AI4SoilHealth and BENCHMARKS), the number and diversity of datasets of soil degradation processes will further increase in the upcoming years. Also, the temporal coverage (including seasonal, annual and multi-annual trends) and the spatial coverage (including all types of land uses in rural and urban areas) of these datasets will increase.

The data and metadata resulting from these soil monitoring activities of Mission Soil projects will be shared according to the FAIR data principles (Wilkinson et al., 2016) through the SoilWise Data and Knowledge Hub. The Mission Soil projects will also develop distinct frameworks for soil health assessment, possessing a specific role, application and scale regarding soil monitoring (e.g. Campbell et al., 2025). Combined, this will result in a better monitoring and spatial assessment of the state of soils in the EU through action on the ground (bottom-up approach, see Panagos et al., 2024a). These datasets will be added to the European Soil Data Centre (ESDAC) (Panagos et al., 2022b) and, if relevant, to the EUSO Soil Degradation Dashboard.

Next to that, on the long-term, the harmonised soil health monitoring framework put in place by the SMRD will be of high importance for monitoring further changes in soil health in the EU. The SMRD will put in place a comprehensive soil health monitoring framework across MS, building on LUCAS Soil sampling strategy. The SMRD will request MS to measure every six years soil properties to assess the status of soil health. As part of reporting obligations, MS will have to undertake a trend analysis of each soil health descriptor, reflecting non-binding thresholds that determine whether soils are in good, moderate or poor condition. This will allow a more systematic monitoring of changes of soil health across the EU. However, the current assessment of soil degradation provided by the EUSO Soil Degradation Dashboard may need to be revised as most thresholds will be set by MS. The SMRD will also help to reflect on the status and trends of soil degradation indicators after multiple monitoring cycles. It will also allow a time lapse longer than a few years; necessary to detect clear trends. Moreover, the SMRD suggests that MS mitigate land take, and that they support land managers to improve soil health and reduce soil degradation. A harmonised soil health framework will also be crucial to provide data and support to land managers, such as farmers, landowners and policymakers in implementing sustainable soil management practices. In addition, an improved access to soil monitoring data allows stakeholders to make evidence-based decision, increases public awareness on soil degradation, and can directly contribute to research projects (see e.g. Panagos et al., 2025).

The importance of the SMRD is also reflected by the projected evolution of the individual soil degradation indicators (section 6.4). Four out of seven studied soil degradation indicators are expected to deteriorate in the upcoming decades (see section 6.4 and **Table 17**). This is mainly attributed to climate change (soil erosion by water and loss of soil organic carbon), unsustainable management practices (phosphorus excess) and land use changes and urbanisation (soil sealing). Moreover, also other degradation processes, not included in this manuscript, are expected to deteriorate in the upcoming decades without changing management practices, due to climate change and increased anthropogenic pressure (see e.g. Afshar et al., 2026; Arias-Navarro et al., 2024). This also highlights the importance of the EU Soil Strategy, the Mission Soil and the SMRD, and an effective implementation of this strategy and directive in national and regional policies in MS. These policy actions are highly needed to continue the investment in soil monitoring and soil research and to accelerate the implementation of sustainable soil management practices, and to bring all indicators on track to reach the target of healthy soils in 2050.

Figure 29. Timeline highlighting key stages of soil monitoring and key policy actions for soil protection, at the EU-level.



Source: JRC analysis.

Table 17. Status, trends and outlook of the soil degradation indicators discussed in this report.

Soil degradation process	**Indicator**	**Status** (% of unhealthy soils)			**Trends** (progress towards target)		**Outlook towards 2050** (progress towards target)	**References**
		for area with data	in the EU	year of assessment	direction	time period concerned		
Soil erosion	Water erosion	23	19	2016	**on track**	2000-2023	**reverse trend**	Panagos et al., 2020, Borrelli and Panagos, 2026
	Harvest erosion	3	1	2000-2016	**on track**	1987-2016	**on track**	Panagos et al., 2019
Soil nutrients	P deficiency	21	8	2009	**on track**	2009-2018	**on track**	Van Eynde et al., under review
	P excess	10	4	2009	**reverse trend**	2009-2018	**reverse trend**	Van Eynde et al., under review
Loss of SOC	Δ SOC	53	14	2018	**reverse trend**	2009-2018	**reverse trend**	De Rosa et al., 2024; Lugato et al., 2021
Acidification	Soil pH indicator			2018	stable	2009-2018	stable	Yunta et al., under review
Soil sealing	Built-up areas	2.7	2.7	2018	**reverse trend**	2006-2018	**reverse trend**	Copernicus, 2018; Perpiña et al., 2019

Source: JRC analysis.

6.6. Conclusions

In this chapter, trends over the past decades and an outlook towards 2050 for seven soil degradation indicators were presented. Results suggest that three indicators (soil erosion by water, harvest erosion and phosphorous deficiency) have improved in the past decades, being on track to reach a healthy state by 2050. More precisely, results show that the mean soil loss from water erosion in the EU in the period 2000-2023 decreased by 13.8%. Secondly, the soil loss due to harvest erosion decreased by 37% between 1987 and 2016. And thirdly, the percentage of unhealthy soils in the EU regarding phosphorus deficiency decreased from 11.2 to 4.9% between 2009 and 2018. However, the three other indicators have showed a reverse trend in the past decade, being off track to reach the objective of healthy soils by 2050. Soil organic carbon content in cropland decreased by 0.75% in the period 2009-2018. Soil phosphorus content increased in the same period by 12.2%. And soil sealing in the EU increased in the period 2006-2018 with 3.4%. No clear trends were found regarding soil pH. The precise role and impact of the Mission Soil and the EU Soil Strategy for 2030 for the described trends could not be assessed, as the available datasets only partially cover the period since the start of these policy initiatives.

Projections towards 2050 show that four studied soil degradation indicators are expected to deteriorate in the upcoming decades with unchanged management practices, mainly caused by climate change and urbanisation. This illustrates the importance of the SMRD, the EU Soil Strategy for 2030 and the Mission Soil to continue the investment in soil monitoring, soil research and innovation, including improving soil literacy and knowledge sharing, and to accelerate the development of recommendations to MS and the uptake of sustainable soil management practices. These continued efforts are needed to bring all indicators on track to reach the target of healthy and resilient soils by 2050.

7. Conclusions

Soil governance and policy

The evolution of EU soil governance over the past two decades reflects a profound transition from fragmented, largely sectoral interventions toward an increasingly integrated and systemic policy framework. What began as a predominantly diagnostic and threat-based approach to soil protection has gradually matured into a broader vision centred on soil health, resilience, and long-term stewardship. This transformation has been driven by the convergence of scientific evidence, mounting socioeconomic pressures, and the recognition that healthy soils are indispensable for achieving strategic objectives related to food security, climate neutrality, biodiversity conservation, and human well-being. Recent developments – including the EU Soil Strategy for 2030, the SMRD, and the integration of soil objectives across the CAP and the EGD – signal a decisive move toward outcome-oriented governance based on harmonised targets, accountability, and restoration commitments. Yet, significant challenges remain, including uneven implementation capacities among MS, limited coordination across institutions and policy sectors, and the need to balance harmonisation with subsidiarity. The future of soil governance in Europe will depend on the ability to strengthen cross-sectoral policy coherence, mobilise adequate financial incentives, and embed soil stewardship more deeply into territorial planning and economic decision-making. Ultimately, effective soil governance must evolve beyond regulatory compliance toward a shared societal commitment to safeguarding soil as strategic natural capital.

Soil data and knowledge infrastructures

The transformation of soil data systems in Europe illustrates how advances in digital infrastructure, data harmonisation, and open-access knowledge platforms have fundamentally reshaped the capacity to understand and manage soil resources. The progression from static soil inventories and fragmented national datasets toward interoperable, multi-source, and policy-oriented information systems marks a major scientific and institutional achievement. Platforms such as ESDAC, LUCAS, and EUSO have established the foundations of a European soil knowledge ecosystem capable of integrating field observations, remote sensing products, modelling outputs, and emerging big-data streams into coherent decision-support tools. This evolution has greatly enhanced the transparency, comparability, and usability of soil information for research, governance, and land management. At the same time, the rapid expansion of data sources introduces new challenges related to interoperability, uncertainty, quality assurance, and equitable access to digital capabilities. Moving forward, the value of soil data will increasingly depend not only on technical sophistication but also on the adoption of FAIR principles, robust governance frameworks, and stronger links between data generation and practical decision-making. In this context, soil data must be understood not merely as a scientific resource, but as critical infrastructure underpinning evidence-based policy and adaptive soil stewardship.

Soil monitoring

Soil monitoring has evolved from periodic and largely descriptive assessments toward a dynamic, increasingly integrated system capable of supporting real-time, adaptive soil governance. This shift reflects both technological progress and a broader conceptual transition from documenting degradation to actively guiding restoration and resilience-building. Contemporary soil monitoring systems now combine conventional field surveys with Earth Observation, proximal sensing, digital soil mapping, and AI, enabling unprecedented spatial and temporal resolution in the assessment of

soil health. The establishment of harmonised indicators and monitoring obligations under the SMRD marks a pivotal step in institutionalising this transformation across the EU. Equally important is the emergence of participatory monitoring approaches, including citizen science and LLs, which broaden the evidence base while strengthening stakeholder engagement. Nevertheless, major challenges persist, particularly regarding methodological standardisation, long-term funding, uncertainty communication, and the integration of diverse monitoring networks across scales. To fulfil its transformative potential, soil monitoring must move beyond passive observation and function as an operational early-warning and decision-support system that enables preventive action, evaluates policy effectiveness, and supports adaptive land management. In this sense, monitoring is no longer simply a technical activity – it is becoming a cornerstone of resilient and accountable soil governance.

Soil literacy and societal engagement

Achieving healthy soils by 2050 will require not only stronger policies, better data, and more sophisticated monitoring systems, but also a profound cultural transformation in how societies perceive and value soils. Soil literacy has emerged as a critical enabling dimension of this transition, bridging scientific understanding with behavioural change, public participation, and collective responsibility. Across Europe, initiatives led by the EUSO, the Mission Soil, educational networks, and citizen science programmes are helping to transform soils from an invisible environmental substrate into a visible and shared societal concern. This shift reflects an important conceptual evolution: soil literacy is no longer understood solely as the dissemination of knowledge, but as a dynamic social capacity that empowers individuals, communities, institutions, and markets to engage meaningfully in soil stewardship. As awareness grows, so too does the potential for more sustainable consumption patterns, improved land management practices, and stronger political support for soil protection. However, significant gaps remain, particularly in formal education, professional training, and the inclusion of diverse social groups in soil-related dialogue and decision-making. Strengthening soil literacy must therefore become a long-term strategic priority embedded across educational systems, policy instruments, and public communication efforts. Ultimately, the durability of Europe's soil transition will depend on whether society comes to recognise healthy soils not merely as an environmental necessity, but as a shared foundation for resilience, prosperity, and intergenerational responsibility.

Quantitative changes of soil degradation indicators in the EU

Quantitative trend data of seven soil degradation processes were analysed, using EU-scale spatial layers and data points produced from harmonised repeated monitoring surveys. Results show that three indicators, soil erosion by water, harvest erosion and phosphorus deficiency, have improved in the past years or decades, suggesting that the range of unhealthy soils decreased in the same period. Conversely, results suggest that the area with unhealthy soils could have increased due to loss of soil organic carbon, phosphorus excess and soil sealing. No clear trends were observed for soil pH. The temporal coverage of the available datasets only marginally covers the period since the start of the Mission Soil and the EU Soil Strategy. Thus, evaluating the effectiveness of these policy initiatives in protecting soils was not possible in this study. Projections suggest that four studied soil degradation processes will further deteriorate in the upcoming decades due to climate change, continued unsustainable management practices, land use changes and urbanisation. This shows the importance of the Soil Monitoring and Resilience Directive, the EU Soil Strategy and the Mission Soil to continue the investment in soil monitoring and related research and other actions, to accelerate

the implementation of sustainable soil management practices, and to bring all indicators on track to reach healthy soils by 2050.

These dimensions of the European soil transition are strongly interconnected and should be considered as components of a single governance framework rather than as isolated developments. Effective soil governance requires reliable, harmonised, and accessible data infrastructures that provide the evidence base for policy design, implementation, and evaluation. However, data alone cannot demonstrate progress or assess the effectiveness of policy interventions without consistent monitoring systems capable of tracking changes in soil condition, pressures, and responses over time. In turn, robust monitoring frameworks depend on interoperable data platforms, shared indicators, and continuous knowledge generation, while their societal impact relies on effective communication, soil literacy, and stakeholder engagement. Together, governance frameworks, data infrastructures, monitoring systems, and societal capacity form a reinforcing cycle in which improved knowledge enables better decisions, better decisions support sustainable management, and improved management generates new evidence to guide future policies.

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List of abbreviations and definitions

Abbreviations	Definitions
AA	Action Area
AEI	Agri-Environmental Indicator
AI	Artificial Intelligence
AKIS	Agricultural Knowledge and Innovation Systems
BDS	Biodiversity Strategy
CAP	Common Agricultural Policy
conc	concentration
CRCF	Carbon Removals and Carbon Farming
DEM	Digital Elevation Model
EAP	Environmental Action Programme
EC	European Commission
EEA	European Environmental Agency
EIP-AGRI	European Innovation Partnership for Agricultural Productivity and Sustainability
ELSA	European Land & Soil Alliance
ENSA	European Network on Soil Awareness
ESDAC	European Soil Data Centre
ESP	European Soil Partnership
ETRS89	European Terrestrial Reference System 89
EU	European Union
EUSO	European Soil Observatory

Abbreviations	Definitions
FAIR	Findable, Accessible, Interoperable, and Reusable
FAO	Food & Agriculture Organization
FP	Framework Programme
F2F	Farm to Fork
GAEC	Good Agricultural and Environmental Conditions
GDPR	General Data Protection Regulation
GHG	Greenhouse Gas
GloSIS	Global Soil Information System
GIS	Geographic Information Systems
GLOSOLAN	Global Soil Laboratory Network
GSP	Global Soil Partnership
HTS	High-Throughput Sequencing
IR	Infra-Red
ISRIC	International Soil Reference and Information Centre
JRC	Joint Research Centre
LDN	Land Degradation Neutrality
LUCAS	Land Use-Land Cover Area-Frame Survey
LULC	Land Use/Land Cover
LULUCF	Land Use, Land Use Change and Forestry
MS	Member State
NBS	Nature-Based Solutions
NGO	Non-Government Organization

Abbreviations	Definitions
OECD	Organization for Economic Co-operation and Development
RDP	Rural Development Programme
R&I	Research and Innovation
SDGs	Sustainable Development Goals
SMN	Soil Monitoring Network
SMRD	Soil Monitoring and Resilience Directive
SOC	Soil Organic Carbon
STS	Soil Thematic Strategy
TLS	Terrestrial Laser Scanning
UAV	Unmanned Aerial Vehicle
UN	United Nations
UNCCD	United Nations Convention to Combat Desertification
USDA	United States Department of Agriculture
VNIRS	Visible and near-infrared spectroscopy
WoSIS	World Soil Information Service
WRB	World Reference Base for Soil Resources
WSD	World Soil Day
ZPAP	Zero Pollution Action Plan

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