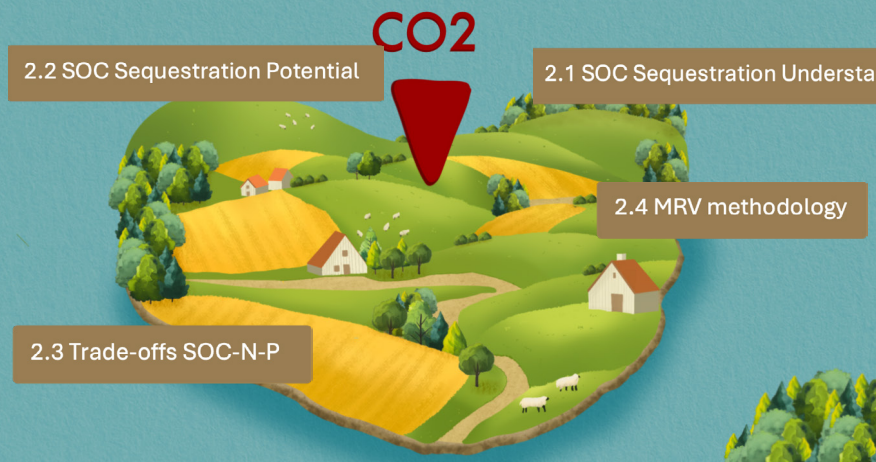
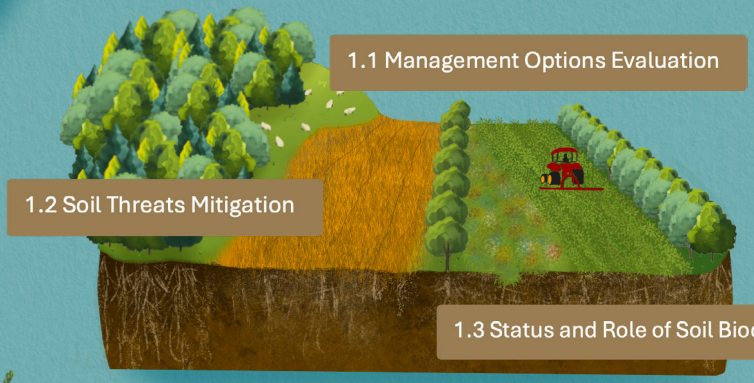
Towards climate-smart sustainable management of agricultural soil

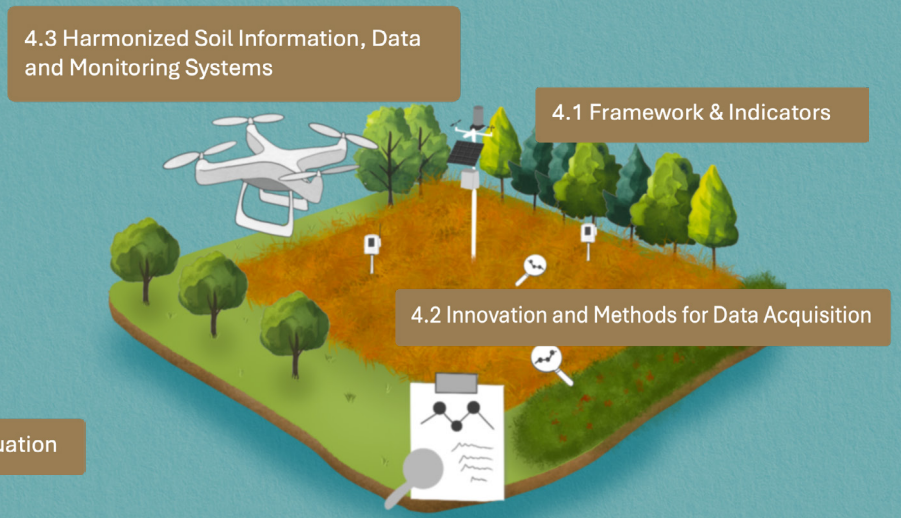
Outputs of the European co-funded research programme EJP SOIL



2. Climate Change Mitigation



1. Sustainable Land Management



4. Soil Information Asessing & Monitoring



3. Climate Change Adaptation



5. Fostering Adoption

Towards Climate-smart sustainable management of agricultural soil

Outputs of the European co-funded research programme EJP SOIL

June 2026

EJP SOIL
European Joint Programme

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1. Sustainable land Management

Soil management is sustainable if the supporting, provisioning, regulating, and cultural services provided by soil are maintained or enhanced without significantly impairing, either the soil functions that enable those services or biodiversity, as defined by FAO (2015). Sustainable soil management enables agricultural soils multifunctionality.

At the start of EJP SOIL, stakeholder consultations identified that the main soil challenges across countries and regions are i) maintaining and increasing soil organic carbon (SOC); ii) maintaining optimal soil structure; iii) avoiding soil erosion; iv) enhancing nutrient retention and use efficiency; v) avoiding soil sealing; vi) enhancing water storage capacity, and vii) enhancing soil biodiversity (Thorsøe et al., 2023). Soil salinization was expressed as a particular challenge in Southern Europe and Turkey.

EJP SOIL has focused primarily on soil organic carbon stocks, soil erosion, soil structure and habitat for soil biota within the internal projects i-SoMPE, SoilCompaC, SCALE, EOM4SOIL and MINOTAUR, and the external projects SoilSymbiotics, WISH-ROOTS, ClimateCropping, SANCHOSTHIRST, AG-ROCOMPOSIT, SOIL-HEAL and CropGas.

1.1 Management options evaluation

The soil-improving management strategies receiving most attention in research and practice across EJP SOIL countries are reduced and no tillage, diversified crop rotations and cover crops, the use of organic fertilizers and amendments, improved nutrient management, and water management practices such as drainage and irrigation scheduling (Paz et al., 2024; Thorsøe et al., 2023). Despite the large body of knowledge available, the adoption of soil-improving management practices remains limited in many European regions (Heller et al., 2024).

A major contribution of EJP SOIL was the mobilisation of European mid- and long-term experiments (MTEs and LTEs), whose characteristics were compiled in a common metadata platform (Donmez et al., 2022; Blanchy et al., 2024). These experiments provide unique opportunities to assess the long-term effects of management practices on soil functions, soil carbon dynamics and ecosystem services across a wide range of pedoclimatic conditions.

Results indicate that conservation-oriented management systems, combining reduced soil disturbance, diversified crop rotations and permanent soil cover, generally provide the most balanced outcomes for soil multifunctionality (Cadel et al., 2023). Cover crops were shown to enhance soil organic carbon accumulation and biological activity (e.g. Fohrafellner et al., 2024), while reduced and no-tillage systems often increased carbon stocks in surface soil layers and improved aggregate stability (e.g. Steponaviciene et al., 2023; Sae-Tun et al., 2022). However, long-term studies also highlighted potential trade-offs, including increased soil compaction or reduced topsoil aeration under no-tillage in some pedoclimatic contexts (ten Damme et al., 2025). The recycling of exogenous organic materials such as composts and digestates is identified as an important strategy to improve nutrient circularity and support soil biological functioning while reducing dependence on mineral fertilizers and a typology of exogenous organic materials is proposed to improve their targeted use (Michaud et al., 2026).

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1.2 Soil threats mitigation

Soil degradation remains a major challenge across Europe, as recently quantified by the JRC. Stakeholders consulted within EJP SOIL identified soil organic carbon loss, soil compaction, peatland degradation and soil erosion among the most pressing soil threats, although their relative importance varies across pedoclimatic regions (Thorsøe et al., 2023). While erosion is particularly critical in Mediterranean and mountainous regions, compaction is increasingly recognised as a widespread threat in intensive agricultural systems. Recent policy developments, including the EU Soil Monitoring Law, reflect growing awareness that preventing soil degradation is essential for maintaining soil functions, food security, climate regulation and ecosystem resilience.

Within EJP SOIL, research on soil threat mitigation mainly focused on soil compaction and water erosion, two degradation processes that directly affect soil productivity and ecosystem services.

Subsoil compaction emerged as one of the most challenging forms of soil degradation because of its persistence and the limited capacity of soils to recover naturally. A synthesis of long-term experiments and literature showed that recovery is generally slow and often incomplete, particularly below the plough layer (Bakema et al., 2023). Biological processes such as root growth and soil fauna activity can contribute to structural regeneration, but recovery strongly depends on climate, soil texture and management. EJP SOIL projects also improved compaction risk assessment through harmonised indicators, modelling approaches and decision-support tools, providing a stronger basis for preventive management. Prevention remains far more effective and economically viable than remediation once compaction has occurred.

Research on soil erosion highlighted the importance of sediment and water connectivity at landscape scale. Erosion is controlled not only by local soil properties and management, but also by the degree to which water and sediments are connected from source areas to streams and downstream environments. EJP SOIL projects demonstrated that integrating landscape connectivity into erosion assessments substantially improves the identification of critical source areas and sediment transport pathways (Schmaltz et al., 2024). New approaches were proposed to incorporate connectivity metrics into erosion models and monitoring frameworks, leading to more realistic assessments of erosion risks and off-site impacts. The work also highlighted opportunities to better integrate scientific knowledge into land management planning and policy instruments.

Overall, EJP SOIL improved understanding of the processes driving soil compaction and erosion, strengthened assessment tools and identified practical pathways to reduce degradation risks. The results underline the importance of preventive soil management and landscape-scale approaches for protecting soil functions and ensuring the long-term sustainability of European agricultural systems (Suleymanov et al. 2026).



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1.3 Status and Role of Soil Biodiversity

The current status and trends in soil biodiversity across Europe are poorly known EJP SOIL projects focused on modelling and mapping soil biodiversity patterns and functions across Europe, and on the soil microbiome in the rhizosphere and on symbiotic microorganisms or inoculated microorganisms (e.g. Oberholzer et al. 2024).

Research consistently identifies soil organic carbon (SOC) as the central metabolic regulator and physical habitat that mediates the functionality of the soil microbiome (Viaene et al., 2025; Raffa et al., 2025).

Management options including the application of Exogenous Organic Matter (EOM), continuous soil cover, and reduced tillage boost soil life by providing metabolic energy and preserving structural niches (EOM4SOIL, 2024; Oberholzer et al., 2024; Ocvirk et al., 2025).

A key output across the programme is that experimental site location (pedoclimate and soil type) often outweighs the effects of agroecological intensification (Doyeni et al., 2024; Raffa et al., 2025). The availability of data limits the establishment of assessment criteria for bioindicators (Riggi et al., 2025).



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2. Climate change mitigation

Soils represent the largest terrestrial reservoir of organic carbon and the balance between soil organic carbon (SOC) formation and loss is expected to drive powerful carbon-climate feedbacks. Agricultural soils have lost huge amounts of organic C since the advent of agriculture and continue losing C in many European locations. Preserving current soil organic carbon stocks and increasing them in agricultural soils, in addition to the effective reduction of N2O and CH4 emissions from agriculture, required progress in five areas:

- Understanding the mechanisms and drivers behind C sequestration in soils and GHG emissions from agricultural soils.
- Evaluating the effect of individual and combined soil management options on C sequestration in soils and GHG emissions and providing realistic estimates for SOC storage potential across EU agricultural soils.
- Identifying, understanding and predicting trade-offs between C sequestration and GHG emissions from agricultural soils.
- Measuring, reporting, and verifying (MRV) SOC stocks and GHG emissions.

A large number of projects were developed on this theme: CarboSeq, MixRoot-C, MaxRoot-C, INSURE, TRACE-Soils, SOMMIT, EnergyLink, AgroEcoSeqC, EOM4Soil, STEROPES, Probefield, Freacs, SIC-SOC-DYN, C-arouNd, TilSoilC, CarboGrass, SOMPACS, TRUESOIL, ICONICA.

2.1 SOC sequestration understading

Soil organic carbon (SOC) stocks depend on the balance between organic matter inputs—from net primary production, residues, and amendments—and losses via mineralization or erosion. EJP SOIL focused on the role of the “microbial carbon pump,” where Microbial Carbon Use Efficiency (CUE) determines the fraction of C stabilized as microbial necromass (He et al., 2024 ; 2026). High CUE supports the *in-vivo* stabilization pathway, turning microbial residues into Mineral-Associated Organic Matter (MAOM), which persists for decades or centuries (Schroeder et al., 2024; de la Rosa et al., 2026).

Below-ground inputs from roots and rhizodeposits are critical, acting as major precursors for organomineral associations (Raffa et al., 2025; Poeplau et al., 2024). Agroecological intensification, including diversified cropping and cover crops, improves aggregate stability and C accrual (Doyeni et al., 2024; Fohrafellner et al., 2024). These systems promote “plant–soil synchrony,” aligning nutrient supply with demand to reduce losses and maximize sequestration (Fontaine et al., 2023).

These processes are limited by environmental filters. Soil pH regulates CUE through a U-shaped relationship (Schroeder et al., 2024). Priming effects also vary depending on residue inputs and management intensity (Liang et al., 2023 ; Dong et al. 2026). Significantly, the traditional carbon saturation theory was challenged, suggesting that SOC accrual is often limited by “ecosystem capacity”—the potential for photosynthetic C inputs—rather than a finite limit of mineral surfaces (Heinemann et al., 2025; Poeplau et al., 2024 ; Begill et al. 2023, 2025).

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2.2 SOC sequestration Potential

Accurate and reliable estimation of soil organic carbon (SOC) sequestration potential is a prerequisite for Member States to define and achieve climate targets under the Paris Agreement and the European Climate Law (Chenu et al., 2026; Don et al., 2024). Scientifically, it is essential to distinguish between SOC accrual, which refers to any increase in C mass within a specific soil volume, and SOC sequestration, which specifically denotes the net transfer of atmospheric into the soil, resulting in a sustained increase in global stocks compared to a business-as-usual reference scenario (Don et al., 2024, Don et al. policy brief).

The EJP SOIL has addressed the heterogeneity of previous national estimates (Rodrigues et al., 2021). Three complementary methodological Tiers were deployed (Chenu et al. 2026): (i) a Tier 2 approach, utilizing practice-specific emission factors (EFs) derived from meta-analyses of over 450 long-term experiments (Panagea et al., 2024; Seidel et al., 2026); (ii) a Tier 3 approach, employing process-based models (e.g., RothC) to simulate temporal trajectories under climate change (e.g. Tao et al., 2023); and (iii) data-driven approaches leveraging machine learning to establish pedoclimatic benchmarks (Pacini et al., 2023; Schneider et al., 2021).

Synthesized results demonstrate that sequestration potential is highly dependent on management choices and biophysical filters. Biochar application offers the highest and most robust technical potential, but the available resource strongly limits its use (Seidel et al., 2026). Agroforestry provides the second-largest potential (24%–45%), though approximately 90% of this storage occurs in biomass rather than soil (Seidel et al., 2026; Drexler et al., 2021). Regarding Conservation Agriculture, zero tillage is estimated to contribute 11%–15% of the total annual European potential, with an emission factor of 1.11 (Seidel et al., 2026; Panagea et al., 2024). However, long-term trials indicate that tillage-induced gains are often limited to topsoil stratification (0–10 cm) and may be offset by subsoil C losses in humid temperate regions (Apostolakis et al., 2026; Seidel et al., 2026). Other effective measures include cover crops, which significantly increase both mineral-associated (MAOC, +4.8%) and particulate organic carbon (POC, +23.2%) (Fohrafellner et al., 2024), and the inclusion of forage legumes/leys in rotations (Seidel et al., 2026; Panagea et al., 2025).

The transition from theoretical to “achievable” potential must account for site-specific biophysical constraints (e.g., clay content and water availability) and systemic trade-offs (Seidel et al., 2026; Ejaz et al., 2026). For instance, while systems like organic farming and Conservation Agriculture promote soil health, their net C storage can be limited by yield gaps—which reduce residue returns—or offset by increased soil emissions, particularly in clay-rich soils (Ceriani et al., 2026; Don et al., 2025; Seidel et al., 2026).



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2.3 Tradeoffs SOC - N-P

Trade-offs in peatlands and organic soils:

In organic soils, the main trade-off is governed by hydrology. Rewetting drained peatlands is an effective strategy to halt large CO2 emissions from peat mineralization (Koch et al., 2023), but it often increases CH4 emissions due to anaerobic conditions. The INSURE project identified a potential "sweet spot" for water table levels (between -0.5 m and -0.25 m) that reduces CO2 losses without strongly increasing CH4 or N2O emissions (Zhao et al., 2025). In drained fens, N2O emissions can reach exceptionally high values, with emission peaks associated with water table fluctuations (Nielsen et al., 2026). Paludiculture systems can help preserve carbon stocks, but intensive management involving fertilization may offset part of the climate benefits (Nielsen et al., 2024).

Tillage and physical regulators in mineral soils:

Reduced tillage (RT) and no-tillage (NT) are often promoted to increase SOC, but long-term studies indicate that they frequently lead to carbon stratification rather than greater whole-profile SOC stocks (Apostolakis et al., 2026). Their effects on N2O emissions strongly depend on soil texture. In clay-rich soils (>30% clay), NT increased N2O emissions by up to 80% because of reduced gas diffusivity and higher water-filled pore space (ten Damme et al., 2025; Ceriani et al., 2026). In contrast, NT reduced N2O emissions by about 40% in sandy soils (Ceriani et al., 2026). Soil compaction further aggravates these trade-offs by creating anaerobic microsites that stimulate denitrification (Pulido-Moncada et al., 2022; Fouladidorhani et al., 2025).

Organic amendments and nutrient management in mineral soils:

The quality of organic inputs is a key determinant of GHG balances. Results from SOMMIT and EOM4SOIL show that residues with high C ratios, such as cereal straw, reduce N2O emissions through microbial N immobilization (Belleville et al., 2026; Valkama et al., 2024). Biochar and compost emerged as particularly promising options, reducing N2O emissions by 33% and 25%, respectively, while contributing to carbon stabilization (Valkama et al., 2024). However, a global meta-analysis showed that replacing mineral fertilizers with animal manure systematically increases CH4 emissions, potentially offsetting gains from lower N2O emissions (Meng et al., 2024). In hemiboreal regions, cover crops may also trigger large winter N2O pulses during freeze-thaw events when frost-sensitive species are used (Kjær et al., 2026). Selecting frost-tolerant species and carefully managing cover crop termination are therefore important mitigation strategies.

Integrated assessment and modelling:

The complexity of these interactions requires multi-criteria assessment tools. The SOMMIT Index (Calone et al., 2024, 2026) integrates yield, SOC, N2O emissions and nitrate leaching to evaluate management options across thousands of scenarios. Simulations indicate that systems combining moderate organic fertilization, no-tillage and rotations including winter cereals achieve the best overall environmental performance (Calone et al., 2026). While SOC sequestration often generates synergies with biodiversity (Latini et al., 2026), it may conflict with groundwater recharge in dry regions because of higher evapotranspiration from cover crops (Blanchy et al., 2023). Life Cycle Assessments further highlight that the climate benefits of SOC-enhancing practices must account for machinery fuel consumption and emissions associated with the production and processing of organic amendments (CarboSeq, D5.3).

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2.4 MRV Methodology

Robust Monitoring, Reporting, and Verification (MRV) systems are the scientific cornerstone for implementing the EU Carbon Removal Certification Framework (CRCF), the Soil Monitoring Law and the Nature Restoration Law. Effective MRV requires a tiered approach that integrates high-resolution field data, advanced sensing technologies, and process-based modeling.

Sensing tools, including proximal (vis-NIR spectroscopy) and remote sensing (e.g., Sentinel-2), offer low-cost, high-throughput methodologies for mapping SOC stocks at multiple scales (Vaudour et al. 2022; Lonzano-Fondon et al. 2026). However, EJP SOIL research indicates that the accuracy of these tools is highly sensitive to pedoclimatic context. For example, remote sensing performance is significantly enhanced by texture-based stratification, Khosravi et al., 2024) and proximal sensing is sensitive to carbonate content and moisture (Castaldi et al. 2023).

Modeling the evolution of SOC stocks is central to MRV, with process-based models such as RothC being deployed to simulate soil long-term trajectories (Tao et al., 2023; Keel et al. 2024). Innovative data-driven reciprocal modeling has also emerged as a powerful tool to predict site-specific SOC changes by leveraging national soil inventory data (Emde et al., 2025; Schneider et al., 2021).

Technical challenges remain for standardized verification. Reliable stock estimates depend on rigorous corrections for soil bulk density and rock fragment content, which are frequent sources of systematic error (Harbo et al., 2022). Finally, comprehensive MRV must extend beyond the topsoil; excluding subsoil dynamics (below 30 cm) may overlook 20% to 40% of the total management-induced C stock changes, potentially leading to inaccurate climate mitigation claims (Emde et al., 2025; Skadell et al., 2023).



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3. Climate change adaptation

Adaptation refers to changes in human and natural systems in response to actual or expected climatic change and its impacts. EJP SOIL investigated climate changes, including extreme events effects on agricultural soils within several research projects (CLIMASOMA, SoilX, ARTEMIS, SoilSalAdapt).

3.1 Management options evaluation

Soil, crop, and water management at the field and farm levels are studied and modelled to understand how management practices affect soil functions under both current and future climatic conditions (Blanchy et al., 2023; Coucheney et al., 2024). This understanding helps in developing adaptation measures and strategies aimed at increasing the resilience of European agriculture to climatic extremes (Blanchy et al., 2023; Garré et al. 2022; Verhagen et al. 2022).

Importance of soil structure: EJP SOIL research highlights that soil structure is the primary determinant of a soil's ability to act as a climate adaptation tool (Jarvis et al., 2024). A stable, well-developed structure is essential for a "virtuous circle": increased organic inputs foster biological activity (e.g., earthworms), which improves structure, enhances water regulation, and ultimately stabilizes crop yields (Jarvis et al., 2024; Meurer et al., 2020).

Adapting to drought and water scarcity. Increasing SOC is a critical lever against water stress. Modelling suggests that adding just 1% SOC down to a depth of 60 cm could reduce potato yield losses during severe droughts from 16.4% to only 7% (Heinz et al., 2025). Furthermore, sequestering carbon in the subsoil (top 65 cm) can increase annual transpiration by up to 40 mm at the onset of summer droughts (Turek et al., 2023). A modelling work showed that breeding and managing crops for deeper and more effective root systems (ideotypes) can increase grain yields by approximately 7% while simultaneously reducing surface runoff and enhancing subsoil carbon storage (Coucheney et al., 2024).

Managing intense rainfall and flooding. Maintaining a "continuous living cover" (e.g., cover crops and perennial leys) is the most effective strategy for fostering macropore networks that maximize infiltration and reduce surface runoff (Blanchy et al., 2023). Practices like mulching and the use of organic amendments stabilize soil aggregates, significantly reducing the risk of erosion and nutrient leaching during heavy precipitation events (Blanchy et al., 2023).

Synergies, trade-offs, and adoption. While practices like reduced or no-tillage protect topsoil carbon, their impact on water supply can be context-dependent and sometimes contradictory, requiring site-specific implementation (Blanchy et al., 2023; Ten Damme et al., 2025; Apostolakis et al., 2026). Successful adaptation is not purely technical; adoption by farmers is strongly tied to risk awareness and the local socio-economic context (SoilX, Artemis and CLIMASOMA projects)(Galioto et al. 2025 ; Leonhardt et al. 2026). EJP SOIL tools, such as the USSF model, now allow for the dynamic simulation of these long-term structural changes, helping to bridge the gap between scientific theory and field-level adaptation (Jarvis et al., 2024; Feifel et al., 2025).

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4. Soil Information Assessing & Monitoring

As soil is a non-renewable resource, having consistent and accessible information about its condition is essential to prevent soil degradation and support evidence-based policies that promote soil health restoration and sustainable soil management. Within this context, eight EJP SOIL research projects (SIREN, SERENA, MINOTAUR, SenRes, STEROPES, Probefield, FAMOSOS, SOIL-ES), along with a dedicated EJP SOIL work package (WP6), have significantly contributed to the harmonization, organization and storage of soil-related knowledge. During the timeframe of the EJP SOIL programme, the European soil landscape evolved significantly after the launch of the European Soil Observatory (EUSO) in 2021 and of the Mission Soil, the proposal of the Soil Monitoring and Resilience Directive (European Council, 2024) and the prospect of new ESA satellites in 2028.

4.1 Framework & Indicators

A major contribution of the EJP SOIL programme has been the development of a harmonized scientific framework and common terminology to quantify soil health and its provision of ecosystem services across Europe. Effective assessment requires a shared definition of soil health—now widely accepted as the "continued capacity of soils to support ecosystem services"—and its quantification through sets of indicators that are both scientifically robust and policy-relevant. Research conducted within the SIREN and SERENA projects highlighted that while scientific consensus on terminology is high, a significant gap remains between researchers and non-scientific stakeholders regarding complex concepts such as "bundles" or "ecosystem services" (Weninger et al., 2024). To address this, the projects developed a conceptual framework that explicitly links Soil Quality (inherent capacity), Soil Health (current state), Soil Threats (degrading processes), and Soil-based Ecosystem Services (SES) (Cousin & Ungaro, 2024).

A fundamental paradigm shift introduced by the programme is the rigorous separation of indicators representing soil *state* (health) from those representing soil *processes* (threats). For instance, while the Soil Monitoring and Resilience Law (SML) often uses soil organic carbon (SOC) content as a health indicator, SOC loss must be assessed as a dynamic change in stocks over time to accurately represent a threat (Suleymanov et al., 2026). The SERENA project identified "ideal" indicators for key threats and "pragmatic" indicators suitable for immediate European-wide implementation. Furthermore, a new ontology of soil-based ecosystem services and impacts was established (Cadel et al., 2023), revealing that maximizing bundles of services in temperate field crops does not systematically lead to a decrease in agricultural production, thus identifying opportunities for agroecological synergies.

To make these assessments operational for policy, a comprehensive framework for setting targets (desirable values) and thresholds/operational trigger values (critical limits) was developed. Recognizing that these values are context-dependent, four distinct methodological approaches were compared: fixed, reference, distribution, and relative change (Matson et al., 2024). This framework includes a decision-tree flowchart to assist Member States in selecting the most appropriate method based on their data availability and specific pedoclimatic conditions (Matson et al., 2024). The use of Soil Units (stratification by soil type, climate, and land use) is emphasized as a prerequisite for defining meaningful health thresholds (Suleymanov et al., 2026).

The MINOTAUR project significantly advanced the integration of biological indicators into monitoring schemes, which were historically underrepresented. The project recommended a "tiered approach" for the implementation of the EU Soil Monitoring Law, suggesting that Member States adopt a minimum of three biological indicators representing key functional groups: chemical engineers (microbes), biological regulators (nematodes/microarthropods), and ecosystem engineers (earthworms) (Mocali et al., 2024). These indicators were tested using a network of Long-Term Experiments (LTEs) across Europe, demonstrating their sensitivity to management practices such as reduced tillage and organic fertilization, and the current lack of available data to robustly set target and threshold values for bioindicators (Riggi et al., 2025; Aponte et al., 2024).

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4.2 Innovation and Methods for data acquisition

IIn recent years, soil sensing technologies (both proximal and remote) have emerged as a promising solution to speed up and reduce the cost of soil surveys. The current performance of proximal sensing techniques for soil property estimation was evaluated, including the effect of different spectral transformation, model calibration and transfer approaches for soil property estimation using existing soil spectral libraries (e.g. Metzger et al. 2023). SOC content prediction using remote sensing has been improved using temporal mosaics from time series, available information on soil texture, and accounting for soil moisture (e.g. Urbina-Salazar et al. 2021). See also the section “MRV for SOC” of this interactive pdf.



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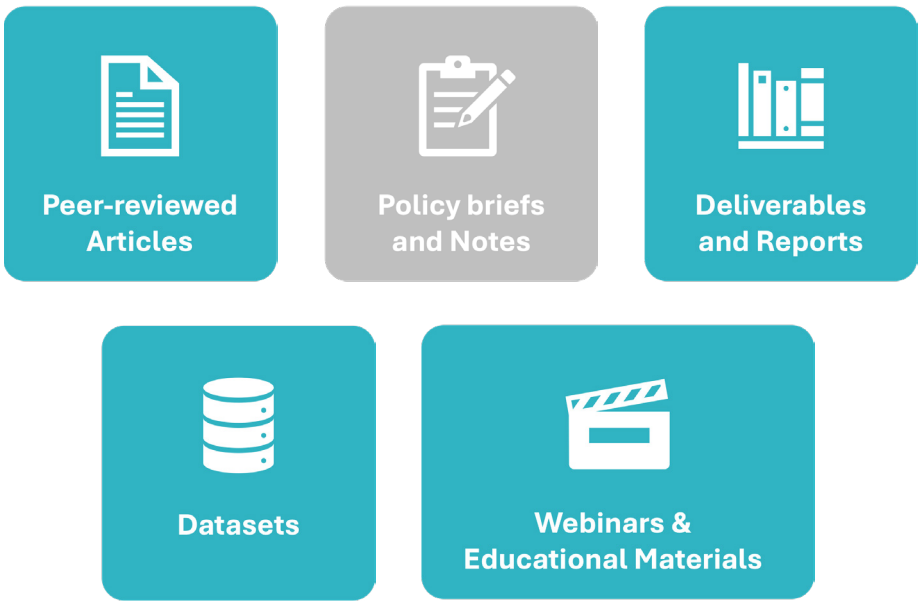
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4.3 Harmonised soil information, data and monitoring systems

While Europe possesses extensive soil datasets, existing information remains fragmented and poorly harmonised across national and INSPIRE portals (Cornu et al., 2023; Fantappiè et al., 2021). A major contribution of the EJP SOIL programme has been the systematic assessment of 25 national soil monitoring systems (SMS) against the requirements of the upcoming EU Soil Monitoring Law (SML), revealing significant variability in sampling designs, protocols, and data accessibility (Mason et al., 2025). Large-scale comparisons between national systems and the EU-wide LUCAS Soil programme highlight that while LUCAS offers a standardised approach, it often oversamples croplands at the expense of woodlands and fails to capture the full range of national soil variability (Froger et al., 2024; Suleymanov et al., 2026).

Research within the programme, including “double sampling” exercises, has demonstrated that differences in sampling protocols such as the tool used, sampling depth, and sub-sampling distance can lead to non-comparable data, particularly for sensitive biological indicators where spatial heterogeneity is high (Del Duca et al., 2025). For instance, establishing robust assessment criteria for soil bioindicators is currently hindered by the lack of standardised sampling and data aggregation protocols across Member States (Riggi et al., 2025). To address these gaps, EJP SOIL developed tools (https://ejpsoil.eu/soil-data/), including a comprehensive metadata catalogue (https://catalogue.ejpsoil.eu/?_gl=1*1hirch0*_ga*MjA1NzMxMjg4My4xNzYzMTM1MjUy*_ga_2NC09FBBZ3*czE3ODE4Njk5NDAkbzc5JGcxJHQxNzgxODY5OTUwJGo1MCRsMCRoMA) that is now taken over by the SoilWise HE project, and proposed a harmonisation framework based on transfer functions. This approach allows for the integration of diverse national datasets into a unified European landscape without compromising the continuity of valuable long-term national data sequences (Meurer et al., 2024; Bispo et al., 2024).



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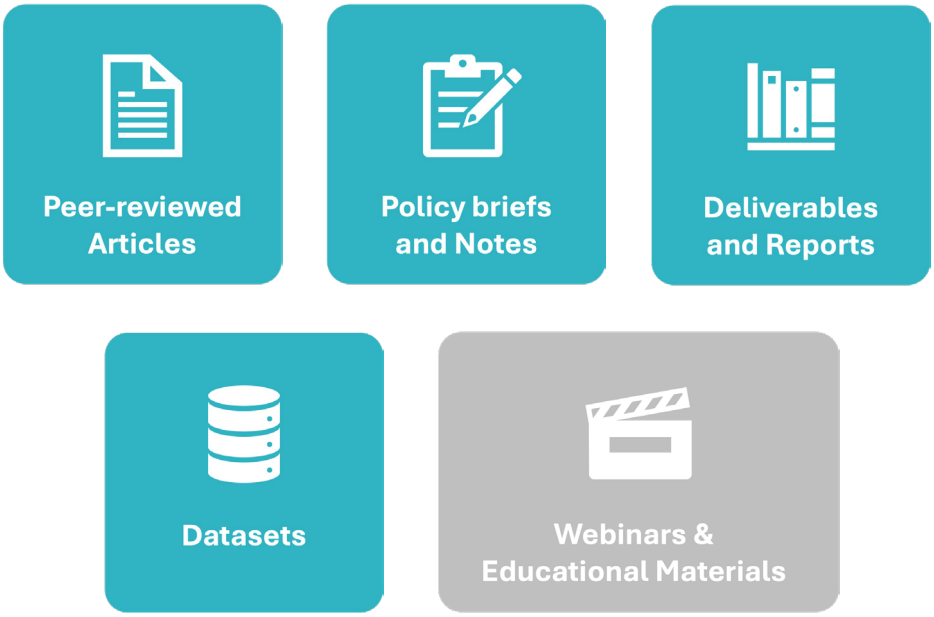
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5. Fostering adoption

Adoption of sustainable soil management options is currently low in Europe (e.g. Heller et al. 2024). Factors limiting adoption of a given management option can be biophysical, but many are socio economic: availability of the knowledge and lack of adequate technical advice, economic constraints and lack of incentives and efficient policies and farming perceptions and traditions (Vanino et al. 2023, Thorsøe et al. 2023). The EJP SOIL programme focused on the science to policy interface and ways to foster adoption. Topics that helped stimulating the knowledge application were for example the evaluation of available tools and available methods for stakeholder engagement and for creating incentives. Projects concerned were in particular iSOmPe, Road4Schemes, SIMPLE, PRAC2LIV, Into-Dialogue and BioCASH and the activity of a dedicated work package.

5.1 Support tools evaluation

To make decisions about soil management that are conducive to soil health, land managers and other stakeholders need reliable information and appropriate tools. Decision Support Tools (DSTs) may serve multiple functions e.g., practical decision making, registration, and monitoring. Substantial differences exist in current fertilisation guidelines across Europe, in the content, in soil test methods and how crop nutrient requirements are calculated, in the format and in their delivery (Higgins et al. 2023).



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Mason, E; Gascuel-Odoux, C; Aldrian, U; Sun, H; Miloczki, J; Götzinger, S; Burton, VJ; Rienks, F; Di Lonardo, S; Sandén, T. 2024. Participatory soil citizen science: An unexploited resource for European soil research. European Journal of Soil Science e13470, (1-17). https://doi.org/10.1111/ejss.13470

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5.2 Tools for stakeholder engagement

Stakeholder engagement is crucial for bridging the gap between scientific research and the practical implementation of sustainable soil management (SSM) practices. EJP SOIL findings demonstrate that current low adoption rates in Europe are primarily constrained by socio-economic factors—such as fragmented communication, inadequate technical advice, and a lack of site-specific incentives—rather than biophysical limits alone (Heller et al., 2024; Thorsøe et al., 2023; Vanino et al., 2023).

To institutionalize the science-policy-practice interface, the programme established National Hubs across 24 countries (Visser et al., 2023; Keesstra et al., 2023). These hubs served as dedicated platforms for over 500 stakeholders to providing input and feedback to the EJP SOIL programme and voicing national specificity and needs, revealing for example distinct priorities such as nutrient efficiency in Northern Europe versus erosion and salinization challenges in the South (Visser et al., 2023). By providing robust baseline data and facilitating continuous dialogue, these hubs actively supported European legislative processes, notably the Soil Monitoring and Resilience Directive proposal (Chenu et al., 2025).

Citizen Science was identified as a powerful but previously under-exploited resource for European soil research (Mason et al., 2024). Projects involving farmers and the general public in the collection of soil health data (e.g., regarding biodiversity and organic carbon) not only generate valuable scientific datasets but also significantly enhance “soil literacy” and environmental responsibility among participants (Mason et al., 2024).

Finally, the transition from linear, top-down research models toward co-construction is facilitated by Living Labs and Lighthouse Farms such as those developed within the EU Mission Soil. These place-based innovation ecosystems allow stakeholders to co-design and test solutions in real-life settings, ensuring that management practices are adjusted to local pedoclimatic and socio-economic realities (Keesstra et al., 2023, Pulido-Moncada et al., 2025). This integrated approach is essential for building trust and increasing the economic viability of the agroecological transition (Pulido-Moncada et al., 2025; Galioto et al., 2025).



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5.3 Incentives and policy evaluation

The EJP SOIL programme has contributed to the evaluation of the European policy landscape and the exploration of incentive structures aimed at facilitating the adoption of sustainable soil managemen (Thorsøe et al., 2023; Keesstra et al., 2023).

EJP SOIL performed a systematic inventory and analysis of carbon farming (CF) schemes, which identified 160 existing initiatives across Europe (Thorsøe et al., 2025; Smit et al., 2024). This analysis revealed that current schemes are predominantly activity-based and funded by public payments, with a significant geographical concentration in Northwestern Europe, highlighting the need for more diversified and regionally tailored approaches (Thorsøe et al., 2025; Galioto et al., 2025).

To strengthen the European Commission's proposal for a Carbon Removal Certification Framework (CRCF), the programme conducted a comparative analysis of international methodologies (e.g., from the USA, Australia, and Canada) (Criscuoli et al., 2024). Key recommendations include expanding the list of eligible practices, setting the Common Agricultural Policy (CAP) conditionality as a regulatory baseline, and implementing "buffer pools" to manage the risks of carbon reversal and leakage (Criscuoli et al., 2024; Paul et al., 2023).

Furthermore, the programme directly supported the development of the EU Soil Monitoring and Resilience Directive by providing baseline data from 24 countries on national soil databases and monitoring networks (Chenu et al., 2025; Froger et al., 2024, and see sections 4.1 and 4.2 of this pdf).

Policy impacts were also analyses through scenario modelling, quantifying the trade-offs of the Farm to Fork strategy's target to reduce mineral nitrogen fertilization by 20% by 2030, and identifying specific European regions where such reductions might impair crop yields and soil organic carbon storage (SIMPLE Policy Brief, 2025; Herrmann et al., 2025).

Collectively, these results emphasize that fostering adoption requires a transition toward result-based payments supported by credible, low-cost Monitoring, Reporting, and Verification (MRV) systems (Heller et al., 2024; Thorsøe et al., 2025).



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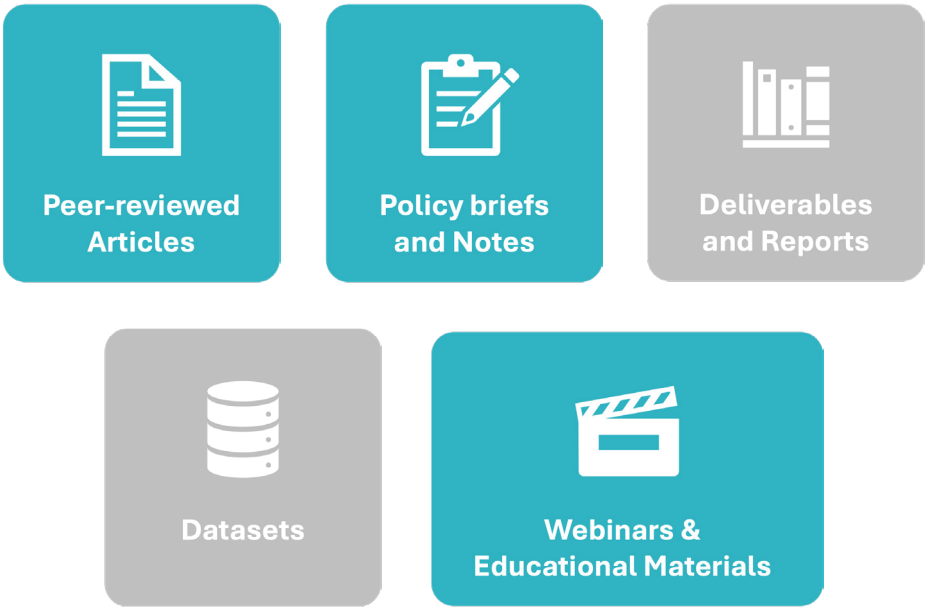
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5.4 Capacity building and education

Sustainable and climate smart management of soils requires human and institutional capacity, expertise and competencies in soil science and agronomy. Soil science related expertise will be more and more in high demand to serve academic, policy and practices of the European Green Deal, the EU Soil Strategy for 2030 and the proposed EU Directive on Soil Monitoring and Resilience. The established baseline of soil science in higher education (Barron and Villa, 2022; Villa et al. 2025) was complemented with an analysis of skills needed in the future for fostering sustainable soil management, and of related professional profiles (Veenstra et al. 2024, Walter et al. 2024).



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