PREPSOIL DELIVERABLE

Title	Analysis of knowledge base available to monitor soil indicators proposed under the Soil Mission
Work package no:	WP5
Deliverable Related no:	D5.1
Deliverable no:	1
Deliverable description:	The deliverable contains overview of soil indicators used in soil monitoring and national experience in monitoring of non-agricultural soil.
Due date:	31.01.2024
Submission date:	12.02.2024
Dissemination level:	PU
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Version:	V1.0

Project acronym: **Project name:**	**PREPSOIL** **Preparing for the 'Soil Deal for Europe' Mission**
Project number:	**101070045**
Call topic:	**HORIZON-MISS-2021-SOIL-01-01**
Type of action:	**HORIZON-CSA**

Funded by the European Union

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Revision history

Version	Date	Reviewer	Modifications
0.1	28.01.2024	Siebielec, Grzegorz; Klimkowicz-Pawlas Agnieszka	First draft
0.2	4.02.2024	Renault, Piere	Comments on first draft
0.3	5.02.2024	Siebielec, Grzegorz; Klimkowicz-Pawlas Agnieszka	Second draft
0.3	7.02.2024	Halberg, Niels	Comments on second draft
0.4	11.02.2024	Siebielec, Grzegorz; Klimkowicz-Pawlas Agnieszka	Third draft
1.0	12.02.2024	Halberg, Niels; Huang, Ning	Confirmation on third draft and final submission

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List of Abbreviations

CEC – cation exchange capacity
EEA – European Environment Agency
EU – European Union
EUSO – European Union Soil Observatory
GHG – greenhouse gasses
LUCAS – Land Use/Cover Area frame statistical Survey Soil
MS – Member States
SOC – soil organic carbon
SQI – Soil Quality Indicators
TOC – total organic carbon

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1 Executive Summary

One of the major Soil Mission components is development of a robust, harmonized soil monitoring framework enabling assessment of policy effects and building information on soil health status trends. In order to develop such a monitoring framework, it is necessary to integrate current knowledge on existing monitoring programs and look for harmonization and improvement of the approaches applied across Europe. One of current gaps in soil monitoring is insufficient coverage of soils located in urban, forest or industrial areas.

The overall objective of PREPSOIL task 5.1 is to contribute to consolidation of the Mission's soil monitoring framework by assessing how to extend the current and upcoming results from other projects dedicated to agricultural soils and existing soil monitoring initiatives to natural, forest, urban and industrial soils.

The task methodology leading to collection of information on agricultural and non-agricultural soil monitoring involved two main phases: phase 1 - a review of selected (completed, ongoing, newly started) projects, supported by the European Commission, dedicated or linked to soil monitoring issues; phase 2 - an inventory of national experiences (national systems, initiatives) on soil monitoring with a special focus on non-agricultural areas. The results of these two phases constitute the basis for a broader discussion on future monitoring of non-agricultural soils. Such a discussion will be carried out in the third phase of the Task 5.1 activity.

In the phase 1, in order to collect knowledge on soil indicators and monitoring, a wide list of completed and ongoing EU projects dealing with soil monitoring was collected. In total 23 projects, initiatives and reports has been compiled and analysed in detail.

In the phase 2 dedicated to existing soil monitoring of non-agricultural soils, the range of information that was collected through stocktaking, such as: general information on the monitoring program; description of soil monitoring (land use, scale, timeframe, type of threat, sampling strategy and density); indicators used (Soil Mission indicators, additional indicators, methodology for measurement or assessment, applied limit values); additional information (gaps/weaknesses of monitoring, recommendation for improvement, data availability). National monitoring procedures implemented in 5 countries have been described as case study examples.

The knowledge delivered here does not exhaust the Task 5.1 content. This state of the art constitutes the basis for dialogue on soil monitoring recommendations to be performed in the next phase of the task 5.1. Therefore, the report will be updated through the dialogue and knowledge exchange with soil experts, other soil related projects, EUSO, etc., including larger geographical representation of ideas for non-agricultural soil monitoring in Member States and Associated Countries.

2 Introduction

The European Mission ‘A Soil Deal for Europe’ is a program of actions aimed at restoration of soil health. The mission will accelerate the transition to healthy soils through ambitious actions in 100 living labs and lighthouses, combined with an ambitious transdisciplinary R&I program, a robust, harmonized soil monitoring framework and increased soil literacy and communication to engage with citizens. Therefore, one of operational objectives of the Soil Mission is to develop an integrated EU soil monitoring system and track progress towards soil health. In order to develop such a monitoring framework, it is necessary to integrate current knowledge on existing monitoring programs and look for harmonization and improvement of the approaches applied across Europe.

The effective soil monitoring is needed to assess policy effects, including the Green Deal policy instruments, and the progress of the Soil Mission. As it was emphasized in the Mission’ implementation plan, current EU wide soil monitoring is hampered by inadequate or inactive soil monitoring programs in many Member States, which results in a lack of data to assess policy options. Even if the data exists, it is not harmonized or incomplete in spatial, temporal, and thematic terms. Furthermore, there is more focus in current monitoring on agricultural soils, whereas less data exists on soils in forests, natural and urban areas.

The Mission has proposed the following categories of soil health indicators to be monitored in order to evaluate soil capacity to fulfil soils’ ecosystem services:

- Presence of soil pollutants, excess nutrients and salts,
- Soil organic carbon,
- Soil structure including bulk density and the absence of soil sealing and erosion,
- Soil biodiversity,
- Soil nutrients and pH,
- Vegetation cover,
- Landscape heterogeneity, and
- Area of forest and other wooded lands.

The proposal of Directive of Soil Monitoring and Resilience was released in July 2023. The objective of the directive is to launch solid and coherent soil monitoring framework for all soils across the EU. It is to be an integrated monitoring system based on EU level, Member State and private data. It shall implement a common definition of healthy soil and constitute a basis for the sustainable management of soils, maintaining and enhancing soil health, and consequently achieving healthy and resilient soils across the EU by 2050.

The PREPSOIL project (Preparing for the "Soil Deal for Europe" Mission) facilitates the deployment of the Soil Mission in European regions. It is achieved through the co-creation and implementation of tools and spaces enabling interaction, knowledge sharing and collaborative learning, as well as assessment and dialogue to understand how regional assessment of soil needs, supported by harmonized monitoring mechanisms, can then lead to activities in living labs and lighthouses for soil health.

The overall objective of PREPSOIL task 5.1 is to contribute to consolidation of the Mission's soil monitoring framework by assessing how to extend the current and upcoming results from other projects dedicated to agricultural soils and existing soil monitoring initiatives to natural, forest, urban and industrial soils.

The specific objectives of task 5.1 are:

- Assess progress and existing gaps in monitoring soils as proposed under the Soil Mission across Europe.
- Evaluate suitability of agricultural soil indicators, including those mentioned in the Soil Mission, and some alternatives, to natural, forest, urban and industrial soils.
- Consolidate and harmonize indicators for various land use types.

This report constitutes the knowledge base currently available on monitoring soil indicators proposed under the Soil Mission collected through integration of information produced in soil related projects and soil monitoring initiatives across Europe. The report does not exhaust the full Task 5.1 content. The intention of the report was to bring state of the art on existing and proposed soil monitoring programs across Europe and across European projects. This state of the art constitutes the basis for dialogue on soil monitoring recommendations to be performed in the next phase of the task 5.1 which will last until project month 24. The report will be updated during the dialogue and exchange with soil experts, soil national hubs, EUSO, soil related organizations in the following months, including larger geographical coverage of Member States and Associated Countries regarding soil monitoring in non-agricultural areas.

3 Methodology

The task methodology leading to collection of information on agricultural and non-agricultural soil monitoring involved two main phases:

1) a review of selected (completed, ongoing, newly started) projects, supported by the European Commission, dedicated or linked to soil monitoring issues;
2) an inventory of national experiences (national systems, initiatives) on soil monitoring with a special focus on non-agricultural areas.

The results of these two phases will form the basis for a broader discussion on assumptions and harmonization needs for future monitoring of non-agricultural soils. Such a discussion, with international organizations (EUSO, EEA), Member States (MS) soil experts, national Soil

HUBs, and EJP SOIL and other projects, will be carried out in the third phase of the Task 5.1 activity.

3.1 Phase 1: Review of the EU projects to collect knowledge on soil monitoring and indicators

In order to gather up-to-date information on soil indicators and monitoring, a set of completed and ongoing EU projects dealing with these issues was considered. Based on the final discussion within the Task 5.1 partners, a list of 23 projects, initiatives and reports was compiled (Table 3.1) and analysed in detail (Appendix 2). In the selection of projects, special attention was paid to those which covered soil uses other than agricultural, e.g. urban, forest, etc.. Moreover, the European soil monitoring programme LUCAS and the recently published report by the European Environment Agency on *'Soil Monitoring in Europe*' (EEA, 2023) were included in the list.

Once the list of projects was agreed, the collection of detailed information about each project was initiated. A Word *'Template - Phase 1*' was developed for this purpose (Appendix 1), consisting of nine separate sections that addressed: I) general project information; II) level of monitoring considered; III) Soil Mission indicators concerned; IV) additional surveys on soil management; V) benchmark values used in soil health monitoring; VI) identified gaps or limitations in soil monitoring; VII) recommendations for the future soil monitoring; VIII) inclusion of non-agricultural soils in monitoring; and IX) additional information.

The final version of the template was achieved through consultation with partners and following their comments on the scope and content of necessary information. The *'Template - Phase 1*' was then circulated to Task 5.1 partners with a request to complete it for each dedicated EU project. Results of these activities formed the basis for the development of the several pages project briefs included in Appendix 2 and the compilation of existing knowledge on, inter alia, soil monitoring and indicators (chapter 4.1).

Table 3.1. List of projects considered in the review (Phase 1).

Project name	Acronym	Funding programme	Land use types addressed	Geographical coverage
Projects completed				
Stocktaking for Agricultural Soil Quality and Ecosystem Services Indicators and their Reference Values	SIREN	Horizon 2020 - EJP Soil internal	agricultural	EU
Land Management Assessment Research Knowledge Base	LANDMARK	Horizon 2020 (CSA)	agricultural	EU
Interactive Soil Quality Assessment in Europe and China for Agricultural Productivity and Environmental Resilience	iSQAPER	Horizon 2020	agricultural	EU

Ecological Function and Biodiversity Indicators in European Soils	EcoFinders	7FP	all types of soils	EU
Providing support in relation to the implementation of the EU Soil Thematic Strategy	Soil4EU	Service for DG ENV	all types of soils	EU
Finding and sharing solutions to protect our soils	RECARE	7FP	all types of soils	EU
Urban Soil Management Strategy	URBAN SMS	Central Europe - Interreg	urban	Central Europe
EU Soil Observatory for Intelligent Land use management	SIEUSOIL	Horizon 2020	agricultural	EU and China
Soil monitoring in Europe. Indicators and thresholds for soil health assessments	EEA report	EEA	all types of soils	EU
Ongoing projects				
Towards climate-smart sustainable management of agricultural soils European Joint Programme	EJP SOIL	Horizon 2020	agricultural	EU
Soil Ecosystem seRvices and soil threats modElling aNd mApping	SERENA (EJP SOIL)	Horizon 2020 (EJP SOIL internal)	agricultural	EU
Modelling and mapping soil biodiversity patterns and functions across Europe	MINOTAUR (EJP SOIL)	Horizon 2020 (EJP SOIL internal)	agricultural	EU
Stimulating novel Technologies from Earth Remote Observation to Predict European Soil carbon	STEROPES (EJP SOIL)	Horizon 2020 (EJP SOIL internal)	agricultural	EU
Holistic management practices, modelling and monitoring for European forest soils	HoliSoils	Horizon 2020	forest	EU
Land Use/Cover Area frame statistical Survey	LUCAS monitoring	JRC/EUROSTAT	mainly agricultural	EU
Soil and water monitoring programme in agriculture	JOVA[a]	Norwegian Department of Agriculture and Food	agricultural	Norway
Projects started in 2022 or 2023				
Operationalising International Research Cooperation on Soil carbon	ORCaSa	Horizon 2020 (CSA)	agricultural	EU
Building a European Network for the Characterisation and Harmonisation of Monitoring Approaches for Research and Knowledge on Soils	BENCHMARKS	Soil Mission HE	all land uses	EU
Accelerating collection and use of soil health information using AI	AI4SOILHEALTH	Soil Mission HE	all land uses	EU

technology to support the Soil Deal for Europe and EUSO				
Boosting carbon farming in central Europe	Carbon Farming CE	Interreg Central Europe	Central Europe soils	EU
Vers un référentiel d'indicateurs de qualités des sols pour l'évaluation et la mise en oeuvre opérationnelle des politiques publiques[b]	IndiQuaSoils	Study supported by the French "GIS Sol"	all land uses	France
Norwegian soil monitoring programme in forests and grazing lands	N.A.	Norwegian Department of Agriculture and Food	forest and pasture land	Norway
Norwegian soil monitoring programme for soil health	JordVAAK	Norwegian department of Agriculture and Food	agricultural	Norway

[a]/ Norwegian project started in 1992; [b]/ in English: Towards a repository of soil quality indicators for the assessment and operational implementation of public policies.

3.2 Phase 2: Stocktaking for experiences in Member States on the monitoring of non-agricultural soils

The main objective of Phase 2 was to collect information available in the different EU Member States on existing soil monitoring programmes or initiatives, especially those on natural, urban, forest and post-industrial sites. For this inventory, another template (Excel working file) was developed and after consultation and evaluation by the Task 5.1 partners was spread among the different MS (PREPSOIL partners, mainly). The range of information that was collected through stocktaking can be divided into few main parts (Table 3.2): 1) general information on the monitoring programme; 2) description of soil monitoring (land use, scale, timeframe, type of threat, sampling strategy and density); 3) indicators (Soil Mission indicators, additional indicators, methodology for measurement or assessment, applied limit values); 4) additional information (gaps/weaknesses of monitoring, recommendation for improvement, data availability).

Table 3.2. Content of the excel template for the Phase 2.

Category	Sub-category	Details
General information	Project/initiative name	
Description of monitoring	Land use type	natural, forest, urban, post-industrial, or all types
	Scale	local (private garden, public park), regional, national, European regional, European, other
	Level of implementation	implemented, strategy defined, planed but not started
	Timeframe	single actions or repeated over time

	Type of threat	erosion, organic carbon loss, nutrient imbalance, acidification, contamination, sealing, compaction, salinization, loss of soil biodiversity
	Sampling strategy and density	soil depth, frequency of sampling; number of samples *per* area
Indicators	Mission indicators	soil pollutants, excess nutrients and salts; soil organic carbon stock; soil structure (soil bulk density), absence of soil sealing and erosion; soil biodiversity; soil nutrients and acidity; vegetation cover; landscape heterogeneity; forest cover
	Additional indicators	
	Methods applied	direct measurement, experimental method, pedotransfer functions, models
	Limit values	threshold, reference, trigger, other value
Additional information	Gaps/weaknesses identified in soil monitoring	
	Recommendations for future/ needs on harmonization	
	Data availability	

Finally, we received completed Phase-2 questionnaires from the following countries: France, Spain, Denmark, Poland. Information on soil monitoring conducted in Norway was added as a result of the Phase 1 implementation. The number of responses may indicate that monitoring of non-agricultural soils (forest, urban or post-industrial) is probably not widely carried out in the other countries, or information on monitoring programmes is not available. This lack of information will be verified during the dialogue phase since the forthcoming Directive on Soil Monitoring and Resilience may stimulate the development of new monitoring strategies and initiatives for all types of soil use in all Member States. Detailed data on current national experience of MS in soil monitoring were described as case studies in chapter 4.2.

4 Synthesis of results

For this report, results of projects closely related to soil indicators and soil monitoring that have been completed or have resulted in the publication of data and recommendations have been deeply analysed.

4.1 Soil monitoring and soil indicators in the previous EU projects

<u>Soil monitoring</u>

The analysis shows that soil monitoring was only directly implemented in some projects (e.g. EcoFINDERS, LANDMARK, MINOTAUR). The task of most projects was /is to establish some conceptual framework for monitoring either soil functions (e.g. LANDMARK, EcoFINDERS) or soil threats (e.g. RECARE) or ecosystem services (e.g. LANDMARK, BENCHMARKS). Depending on the objective, different sets of indicators were assessed/analysed in order to finally propose those best characterising the links between, for example, soil management and soil functions or threats. The recently launched projects (BENCHMARKS, AI4SOILHEALTH) relate directly to soil health, with the expected outcomes being: the development of soil health indicators, recommendations for sustainable practices to support soil health, and the creation of smart tools to monitor soil health metrics.

Some EU projects have not carried out direct research, but using previous results, literature and available databases, an inventory of soil quality indicators and corresponding threshold values (SIREN), as well as soil monitoring systems carried out in EU countries (Soil4EU, EJP SOIL), has been made. These analyses resulted in recommendations for a framework for future monitoring and identification of harmonisation needs in this area; these recommendations are detailed in the next section of the report (subchapter 4.1.1).

The main land use studied in EU projects is related to agriculture (Figure 4.1): 10 projects focused exclusively on agricultural land, 3 considered all types of land use (agricultural, forestry, urban, post-industrial, natural), and forestry and urban land use were the focus of only 3 (LANDMARK, HoliSoils, BENCHMARKS) or 2 (URBAN SMS, BENCHMARKS) projects respectively.

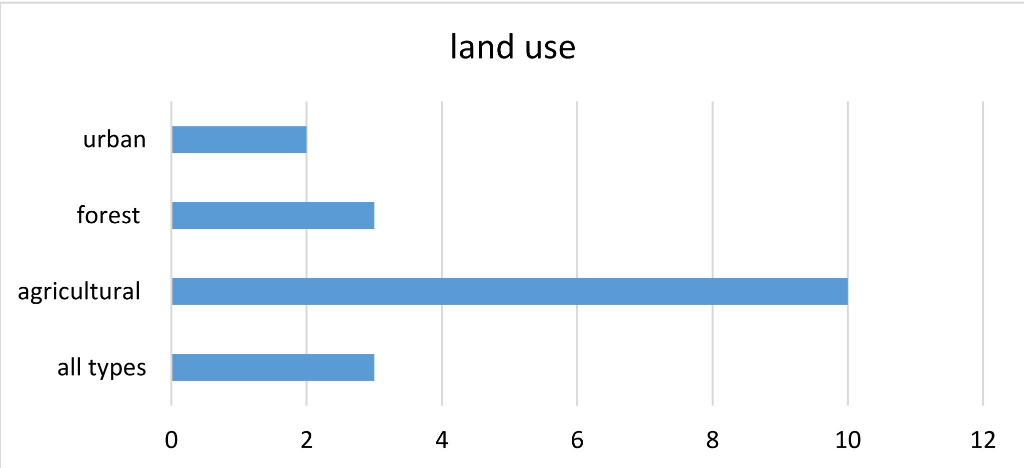

Figure 4.1. Investigated land uses in the EU projects.

The research carried out in the EU projects mostly concerned the European scale, due to the nature of the projects and their international wide coverage in the EU. The differentiation of soil conditions from soil-climatic zones was also taken into account, while in cases where research was carried out at Case Study Sites, soils were monitored at a smaller scale (Figure 4.2).

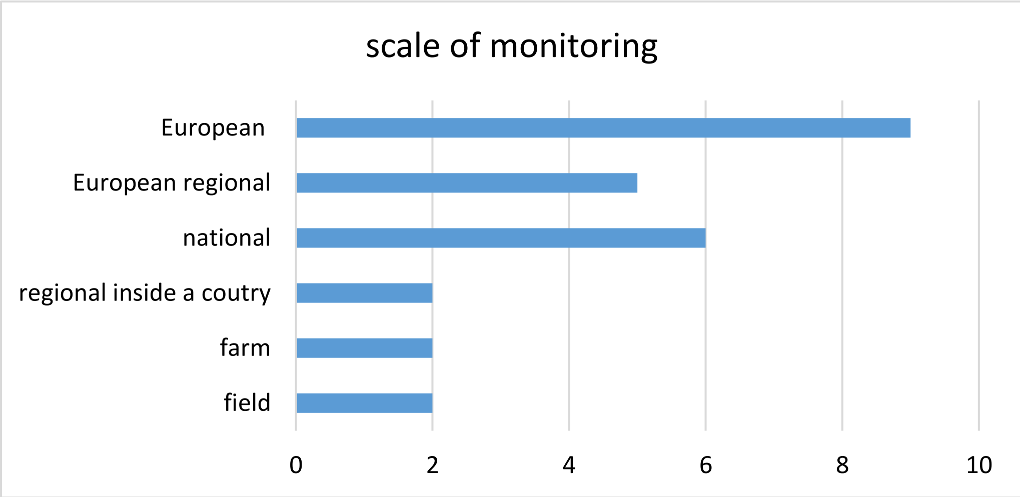

Figure 4.2. Monitoring level considered in the EU projects.

Soil indicators

A general summary of the Soil Mission indicators included in EU projects is presented in Figure 4.3.

Soil organic carbon stocks or content was the indicator most frequently addressed in EU projects, followed by soil nutrients and acidity, and soil structure including bulk density. Of the nutrients, either only essential nutrients (N, P, K, S, Ca) or a whole range of macro- and micronutrients were included.

Soil biodiversity was analysed to varying extents in 11 EU projects. In some, only single indicators of overall soil biological activity were included. In half of these projects, both functional and structural soil biodiversity indicators were analysed, e.g. enzymatic activity, microbial biomass, microbial respiration, carbon mineralization (as functional indicators), and diversity of soil microorganisms (bacteria, fungi, archaea, viruses, algae) and micro-, meso-, macrofauna (as structural indicators). Soil biodiversity has been extensively tested in three completed projects (EcoFINDERS, LANDMARK, iSQAPER) and is currently the subject of the MINOTAUR and BENCHMARKS projects, which aim to select the best indicators for monitoring soil health and develop appropriate reference values for them.

Indicators such as vegetation cover or forest area were taken into account to a lesser extent.

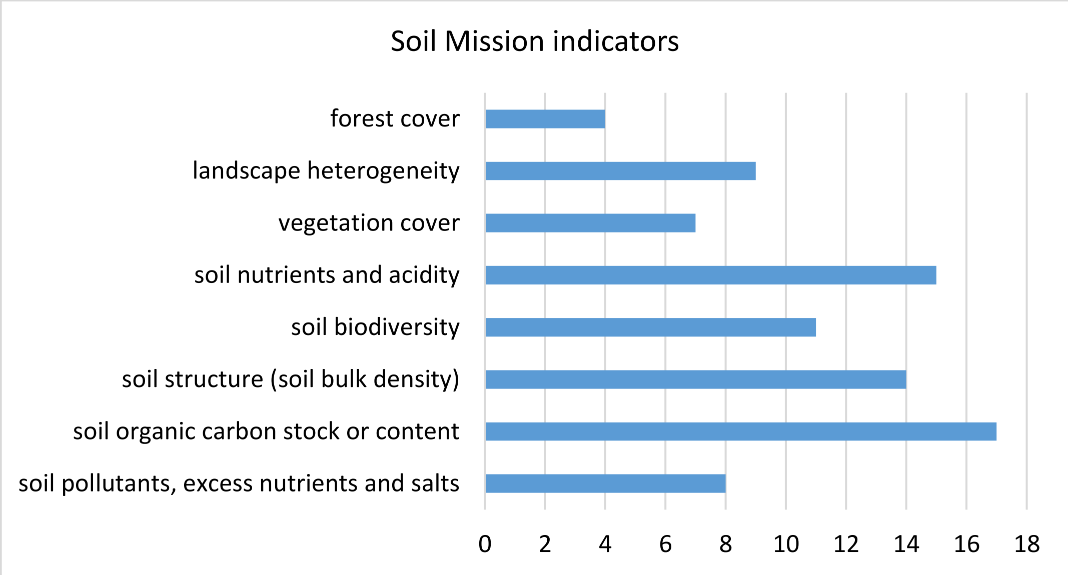

Figure 4.3. Soil Mission indicators mentioned in the EU projects.

In addition to the Soil Mission indicators (listed in Figure 4.3 and Table 3.2), many additional indicators were often analyzed, among others: C:N ratio, drainage class (LANDMARK), soil temperature (LANDMARK, RECARE), labile organic fractions (iSQAPER), soil sealing/land take (RECARE), soil moisture (STEROPES).

Transition index of high quality soils was calculated in URBAN SMS project based on combination of spatial land use change data with soil spatial information. In the newly started AI4SOILHEALTH project the Soil Health Index certification system will be developed to support landowners and policy makers.

Summary of recommendations for improving soil monitoring based on EU projects

Past and ongoing EU project that tackle the issue of soil monitoring commonly recommend standardisation of methods used for analysis of soil status. This refers to both laboratory analytical method and soil sampling methods. Application od various methods for example for monitoring SOC or available nutrient levels make any data harmonisation difficult. The differences often originate from the national approaches applied decades ago when national monitoring programs were initiated in many countries.

In terms of indicators the need to better link indicators with soil functions or soil ecosystem services is highly recommended. The linkage of soil indicators with land production function is relatively better represented whereas there is a strong need to establish and connect soil indicators with such soil ecosystem services as water retention, climate mitigation and adaptation to, biodiversity support, etc. Lack of matching widely used indicators with the range of soil ecosystem services hampers our ability to evaluate the soil contribution to provision of the services or study its trends.

It has been clearly stated that indicators representing soil biology are much needed to enable understanding of soil biodiversity and biological activity role for soil functioning and soil ecosystem resistance. Similarly representation of physical soil indicators shall be improved in soil monitoring to better study the effect of soil management on soil properties that are very important for example for water cycling and retention.

There is a need for policy relevant indicators so that the set of indicators used in soil monitoring might provide information helpful to understand the impact of policies (e.g. agricultural policies) on soil health. The soil indicators shall also help to understand the effects of soil management practices (e.g. tillage, rotation, etc.) on soil health. Often a tiered approach in soil monitoring and soil indicators are recommended: there shall be a minimum dataset (1 level) developed to enable soil health monitoring and harmonisation at EU level. Second level would be more detailed and would address national challenges and specificities whereas 3rd level would be regional and site-specific.

It is required to improve ability of interpretation of soil monitoring results, therefore well-defined target values shall be established and verified. It would be also beneficial to improve linkage between soil monitoring data with socio-economic data, soil management surveys, information on policy instruments applied. One of the weaknesses of current monitoring programs is very limited ability to explain observed strands in soil indicators.

Harmonisation of soil monitoring strategies across EU countries is highly needed since existing programs are very diversified. The existing programs are mostly dedicated to agricultural land and some programs have a long history, dating back to 80s or 90s of 20th century. Therefore it is recommended to cover other land uses by soil monitoring or connect programs addressing different land use types if they exist in one country (e.g. agriculture and forestry). Few countries combines various land uses in one soil monitoring program. The need to identify ways to collaborate between national soil monitoring networks have been raised. That would be especially beneficial in case of transborder collaborations.

The projects emphasize the need to better integrate monitoring of SOC since there are no target values defined, both concerning its content and stock. Therefore it is recommended to develop benchmark values for SOC and the European framework for SOC monitoring. Some project raise the strong need to develop soil monitoring programs and indicators for urban and suburban areas. Such programs do not exist in any significant scale and frequency. The only monitoring programs were rather of polit character and most frequently addressed time driven changes in soil sealing or land take due to urbanisation. The need to use soil information in spatial planning in urban development is emphasised since soil management in urban ecosystems affect living conditions in cities and society’s health.

Some project has raised the need to solve the issue of privacy and personal data in soil monitoring. The inclusion of soil remote sensing and proximal sensing and modelling would be also beneficial to improve soil information especially in the spatial context.

4.1.1 Detailed messages from the completed or almost completed EU projects dedicated to monitoring or indicators

4.1.1.1 EcoFINDERS recommendations

The first pan-European soil biodiversity monitoring scheme was developed as a part of the **EcoFINDERS** project (2011-2014), which aimed to gain knowledge about soil biodiversity in Europe and its associated ecosystem services. Samples were taken from forest, cropland and grassland systems in five European climate zones. Biodiversity indicators were assessed by direct measurements of soil samples according to standard operating procedures developed and refined within the project (Orgiazzi et al., 2016; Griffiths et al., 2016).

Key recommendations from the **EcoFINDERS** project (Griffiths et al., 2016):

- for a large-scale biological indicator programme, standardisation of methods is an absolute necessity, otherwise it is not possible to compare results correctly;
- a set of indicators linking biodiversity to soil functioning is needed;
- precise sampling protocols are necessary;
- a minimum set of indicators of ecosystem function related to water regulation, carbon sequestration and nutrient supply would include: earthworms; microbial functional genes; and bait lamina.

4.1.1.2 LANDMARK recommendations

The **LANDMARK** project (2015 – 2019) comprehensively quantified the current and potential supply of soil functions across the EU, as defined by soil properties (soil diagnostic criteria), land use (arable land, grassland, forestry) and soil management practices. One of the specific objectives was to develop a monitoring scheme for the range of soil functions associated with different soil types, land uses and major climate zones in Europe. Soil indicators used for soil function monitoring were measured according to standard methods, immediately after sampling and laboratory analysis.

The project collected information on soil monitoring systems in 16 EU Member States, assessed sampling schemes, sampling site distribution and sampling frequency. The overall picture highlighted a clearly unbalanced dataset, in which mainly chemical soil parameters were included, while biological and physical soil attributes were severely under-represented. It was shown that the methods used in each country for the indicators also varied. The evaluation of the LUCAS soil survey programme also confirmed the absence of important soil biological parameters such as C mineralisation rate, microbial biomass and earthworm community, as well as soil physical measures such as bulk density.

Key gaps and recommendations (van Leeuven et al., 2017):

- weak representation of biological and physical parameters in EU MS which limits capacity to monitor soil functions;
- large variation between national programs in number of sites, site selection and included attributes, showing a clear lack of harmonisation between national approaches;
- the need to complement the LUCAS monitoring with biological parameters;
- harmonisation of soil sampling and range of analyses in the countries across Europe as a key feature of a coordinated EU-wide soil monitoring.

4.1.1.3 EJP SOIL recommendations

The overall goal of **the EJP SOIL programme** (2021-2025) is to build a sustainable European integrated research system and develop and deploy a reference framework on climate-smart, sustainable agricultural soil management. Work package 6 of EJP SOIL focusses on data management, monitoring soils and mapping soil information.
Within the framework of the EJP SOIL programme, a range of work has been carried out under various packages and in-house projects to inventory the current knowledge of soil monitoring systems (Bispo et al., 2021; van Egmond et al., 2021) and indicators (Pavlů et al., 2021; Faber et al., 2022) used to assess the quality of agricultural soils.
A survey of soil quality indicators was conducted among member states (Pavlů et al., 2021). It showed that the most commonly monitored soil quality parameters include: soil organic carbon concentration and its changes over time, macro-element (N, P, K) and micronutrient (Cu, Mn) content of soils, soil pH, cation exchange capacity and base saturation of soils, soil texture and bulk density, and contamination by potentially toxic elements, especially Cd, Co, Cr, Cu, Ni, Pb and Zn. Assessment of water content is one of the less frequently monitored soil attributes in the participating countries. Contamination by organic pollutants is only considered in about one third of the countries. Biological parameters are generally the least frequently assessed soil quality indicators in Europe. Biological activity is most often assessed on the basis of soil respiration, but again only in 7 participating countries.

According to an inventory by Bispo et al. (2021), most soil monitoring systems in the EU were developed and launched in the 1990s to monitor soil quality. The main land use surveyed is related to agriculture, some Member States (Austria, Belgium, Germany, Hungary, Latvia, Slovakia and Sweden) declared monitoring of forest land, and only a few (Belgium, Austria, Switzerland) of all soil types (natural, agricultural, forest, urban). Soil monitoring systems varied in sampling frequency (4-15 years), number of sites per country (approximately 110-2500 sites), sampling protocols (sampling area from less than 5 m^2 to 1 ha), soil sampling depth (single or multiple depths; 0-10 cm or under 0.5 m). Differences were also found in the number of parameters studied, with organic contaminants and soil communities (i.e. soil biodiversity) poorly monitored.

4.1.1.4 SIREN recommendations

The EJP SOIL internal project **SIREN** (2021 – 2024) aimed to identify and review national approaches (in the 20 countries participating in the SIREN consortium) to make use of soil data in the assessment of soil ecosystem services (Faber et al., 2022). SIREN produced a synthesis of policy-relevant soil quality indicators with high potential for harmonized application in national and European monitoring based on literature, international policy, international stakeholder opinions, wide application in national soil monitoring and EU projects contributing to **agricultural soil quality assessment**.

Within SIREN project a stocktake of indicators used and monitored in the countries was made and the following gaps identified (Faber et al., 2022):

- the use of soil quality indicators in monitoring to assess soil functions is not widely distributed across the participating EJP SOIL Member States;
- the largest commonality in indicators implemented by MS is the quantification of soil organic carbon (stocks and changes);
- there is omission in almost all countries in soil biological indicators, addressing soil biodiversity either with respect to structural aspects (species richness, etc.), or functional aspects (associated with soil functions and provision of services), *or both*;
- indicators for water regulation and persistent organic contaminants are also scarcely implemented, whilst cost-effective methods have come available;
- biological indicators are missing in most European countries;
- national evaluation criteria for soil quality indicators such as references and target values have been implemented scarcely;
- it is difficult to compare reference, target and threshold values because of their dependence on soil type, soil layer, land use, etc.

Table 4.1.1. Indicators (‘minimum data set’) suggested for use at Tier 1 (Faber et al. 2022).

Policy indicators	Soil Quality Indicator
Soil physical condition	Texture
	Porosity
	Bulk density
Soil fertility	C content
	Total N
	P
	K
Erosion evaluation	Based on calculation
Salinity	Electric conductivity
Contamination	Heavy metal trace elements

Other contaminants	Recommended to be included
Soil biodiversity	
Water regulation	

Key recommendations (Faber et al., 2022):

- develop a tiered approach for the implementation of soil monitoring;
- agree on a minimum indicator set for pan-European harmonisation; use indicators currently implemented by >50% of Member States as a preliminary Tier 1 (Table 4.1.1);
- develop benchmark values to support the implementation of EU policies on soil.

A tiered approach to soil quality monitoring proposed by Faber et al. (2022):

- level 1 - includes generic, uniform indicators, used across the EU (="minimum data set"); can be a harmonised element of soil monitoring across the EU.
- level 2 - more detailed monitoring using additional indicators, selected by the Member States themselves according to their specific needs and objectives (regional variation within the EU)
- level 3 - includes modelling, complementing measurements, providing more details at regional and sub-regional scales and supporting site-specific decision-making and management where necessary.

Clearly, for harmonised assessments across EU only 1st tier data may qualify.

4.1.1.5 MINOTAUR recommendations

MINOTAUR (2021 – 2024) aims to provide models, maps and policy-relevant indicators with validated reference values for monitoring soil biodiversity and associated functions. Moreover, it will aim to understand how agricultural practices can contribute to climate change mitigation and adaptation at regional and national levels across the EU. The main aim is to identify and select relevant taxonomical and functional indicators for soil biodiversity and associated soil functions, document their status and trends in time and space across Europe, as well as to assess vulnerability of biodiversity indicators to climate change and sensitivity for management practices.

As a first output from the project, the preliminary recommendations (Table 4.1.2) to the proposed Soil Monitoring Directive was published in the document "*Feedback to the Soil Monitoring Law from the EJP SOIL internal project 'MINOTAUR' on soil biological indicators*". It was indicated, that baseline soil respiration included in the proposal of Soil Monitoring Law is insufficient to soil biodiversity assessment.

Preliminary recommendations from the MINOTAUR project for the future soil monitoring:

- a two "tiered system" approach; a first set of harmonized indicators is recommended in all cases, covering both functional and structural biodiversity, and for which standard methods are available (Tier I group);

- If Tier I results indicate a “not healthy” status, MS may also locally apply other indicators (tier II group), to better identify the problem (soil threats) and/or to inform decision pertaining to land management.

Table 4.1.2. Preliminary recommendations from the MINOTAUR project[1].

Aspect of soil degradation	Current directive Soil descriptor (Annex I)	Recommendation
Loss of soil biodiversity	Soil basal respiration (mm^3 O_2 g^{-1} hr^{-1}) in dry soil Member States may also select other optional soil descriptors for biodiversity such as: - metabarcoding of bacteria, fungi, protists and animals; - abundance and diversity of nematodes; - microbial biomass; - abundance and diversity of earthworms (in croplands); - invasive alien species and plant pests	Tier I group: Functional diversity: - soil basal respiration - microbial biomass; - enzyme activity (fluorogenic substrates); Structural diversity: - metabarcoding of microorganisms (bacteria, fungi); - abundance, diversity and ecological indices of nematodes; - abundance, diversity and ecological indices of microarthropods; - abundance, diversity and ecological indices of earthworms; Member States may also select other optional soil descriptors for biodiversity (Tier II group), such as: - specific groups and functional genes (qPCR) - soil metagenomics for biomarkers of soil health - microbial necromass - Soil fauna activity (i.e. organic matter degradation) - N mineralization - ecophysiological profile (AWCD) - invasive alien species and plant pests

[1]/Source:https://ejpsoil.eu/fileadmin/projects/ejpsoil/WP8/Soil_monitoring/2023-11-03_EJP_SOIL_Feedback_to_Soil_Monitoring_Law___MINOTAUR___Biological_Indicators.pdf

4.2 National monitoring procedures and indicators used across EU for non-agricultural soils

In response to our survey, five countries described their national monitoring systems (15 in total) designed to investigate either single (forest, agricultural) or all types of land use (agricultural, urban, post-industrial, forest, natural).

4.2.1 Case study 1 – France

France has a very comprehensive Soil Quality Monitoring System called "*Réseau de Mesures de la Qualité des Sols*" (RMQS) designed to investigate **all types of land use** (including agricultural, urban, post-industrial, forest, natural) (case study 1.1, Appendix 3). RMQS started in 2000 and every 12 – 15 years, soil sampling, measurements and observations are made at 2241 sites across the country, which are spread evenly across of a 16 x 16 km grid. All sites are georeferenced and 4 composite samples (for 0-25 cm, 25-50 cm, 50-75 and 75-100 cm) made each of 25 sub-samples are taken from the area of 400 m^2. Sampling for bulk density is made in a soil pit at three depths. The following Soil Mission indicators are addressed in this system: soil organic carbon stock, soil structure including soil bulk density, soil biodiversity, soil nutrients and acidity (pH), vegetation cover, landscape global description, forest cover. Limit values (threshold values) are used only for heavy metals based on the regulation for the sewage sludge. Additional information on soil management (rotation, soil tillage, fertilization, irrigation) are collected. Data from RMQS are partly freely available.

Two other monitoring programmes (BDAT, BTETM) carried out in France are designed to assess only **agricultural soils** (case study 1.2 and 1.3, Appendix 3). Data on organic carbon, soil pH, nutrient content (BDAT) and contaminants (BTETM) are collected every 5 or 10 years respectively; the sampling strategy varies depending on the laboratory responsible for implementing the soil monitoring. Soil organic carbon stock, soil nutrients and acidity (pH) and presence of soil pollutants, excess nutrients and salts are Mission indicators included in BDAT and BTETM monitoring programme. Results of both BDAT and BTETM are available only with permission of the responsible laboratory.

4.2.2 Case study 2 – Spain

Spain has mentioned several monitoring programmes addressing **all types of land use** (case studies 2.1, 2.3, 2.4, 2.5, 2.6, Appendix 3) and **natural-forest land** (case study 2.2, Appendix 3). One programme *'Inventario Nacional de Salud del Suelo*' (MITECO-TRAGSA) i.e. National Inventory of Soil Health is the very beginning stage and under construction. This system will cover monitoring of all soil threats (erosion, organic carbon loss, nutrient imbalance, acidification, contamination, sealing, compaction, salinization, loss of soil biofiversity) in **all types of land use**.

Currently ongoing monitoring systems: Environmental Profile of Spain (PAE), National Soil Erosion Inventory (*Inventario Nacional de Erosión de Suelos,* INES), Environmental Information Network of Andalusia refer mainly to the monitoring of soil erosion at national and regional level in **all kind of land use**. These programmes are usually carried out every 10 years and mainly cover the Soil Mission indicators: soil structure including soil bulk density and absence of soil sealing and erosion, landscape heterogeneity, presence of soil pollutants. To evaluate 'soil loss by erosion process' the following reference values are applied: 'Moderate' soil loss is defined as 0–10 t/ha/year, 'Intermediate' as 10–25 t/ha/year, and 'High' as over 25 t/ha/year.

Natural-forest land is included in Spanish monitoring under the '*Estrategia Nacional de Lucha contra la Desertificación*' (ENLD), i.e. National Strategy to Combat Desertification, in which the assessment of desertification and vegetation cover (Mission indicator) is repeated over time at national and regional level.

4.2.3 Case study 3 – Denmark

The Agricultural Soil Sampling Grid in Denmark (Kvadratnettet) was established in 1985 based on a 7 x 7 km^2 grid to monitor the nitrogen content in the soil on a national basis. At each grid area sampling were made at four soil depths; 0–25, 25–50, 50-75 and 75-100 cm. In total 820 sites were sampled. 608 of these were on **agricultural land**, 55 on **perennial grassland**, 46 in **deciduous forest**, 60 in **conifer forest**, 16 on **heathland**, 5 on **wet natural land** and 30 on other land (Østergaard and Mamsen, 1990). The sampling points are mainly used for measuring the content of mineral N, but a part of the points have also been revisited to analyse the content of C as well as P. The data set on soil C measurements was established over a period spanning 22 years, i.e. with soil sampling and analytical campaigns in 1986-1987, 1997-1998, and 2009-2010. In addition, information on the land use and management was collected through farmers interview, details can be found in Appendix 3 (case study 3). The following Soil Mission indicators were monitored: soil organic carbon content, soil bulk density, soil nutrients (N, P, mineral), vegetation cover, soil water retention.

4.2.4 Case study 4 – Poland

Poland has a soil monitoring system called '*Monitoring Chemizmu Gleb Ornych Polski'*, i.e. Monitoring of Arable soils of Poland (Appendix 3), started in 1995, managed by Chief Inspectorate of Environmental Protection and included in the State Monitoring of Environment. The main goal of this system is designed to track changes in various properties of **agricultural** soils that occur over the years as response to agricultural and non-agricultural human activities. Soil samples are collected from the 0 – 20 cm soil layer every 5 years in 216 permanent control points. All sites are georeferenced (precision depends on GPS devices) and a composite sample is taken from an area of 100 m^2 (square 10 x 10 m, 20 subsamples collected). The wide range of chemical propeties is monitored every five years, which cover the following Soil Mission indicators: presence of soil pollutants (trace elements, polycyclic aromatic hydrocarbons - PAHs); soil organic carbon content; soil nutrients (N, P, K, Ca, micronutrients) and acidity (pH), vegetation cover. Reference values are applied to the pollutants monitored, such as: trace elements and PAH compounds. The full monitoring dataset is publicly available through the monitoring website.

Under the State Monitoring of Environment, the **forest monitoring** is also carried out. This monitoring includes permanent Level I and Level II observation plots dedicated to the assessment of morphological characteristics, damage, species diversity and stand condition; these observations are usually carried out periodically every 4-5 years. This monitoring is carried out by the Forest Research Institute. Soil surveys, i.e. chemical properties, soil typology, granulometric composition, physical properties, are also carried out on permanent Level II plots. In addition, air quality, rainwater quality and quality of soil solutions are assessed on a monthly basis on intensive monitoring plots (12 plots). In these 12 plots, soil temperature (at 5 cm, 10 cm, 20 cm and 50 cm depth) and soil moisture are determined. In soil solutions, the following are analysed: Cl^{-}, NO_3^{-}, PO_4^{3-}, SO_4^{2-} and NH_4^{+} ions, macro- and micronutrients, pH, electrical conductivity.

4.2.5 Case study 5 – Norway

The Norwegian **Agricultural** Environmental Monitoring Programme (JOVA) is a national programme for soil and water monitoring in agriculture dominated catchments in Norway (Appendix 3). JOVA was initiated in 1992 with the aim to document the effects of agricultural practices and measures on runoff and water quality. In total, 13 catchments are monitored. In most of them, there is a continuous record of water-flow and sampling for analysis of nutrients, particles and pesticides. During the monitoring period, JOVA has established a database with long time-series of data for nutrient runoff, soil erosion, pesticide loss and agricultural management practices. JOVA programme include the several Mission indicators: presence of pesticides, soil organic carbon content, erosion, soil nutrients and acidity.

Norway has also national monitoring of soil organic carbon (SOC) programme in **forests and grazing lands** newly started in 2023 and scheduled to occur over two 10-year cycles. This monitoring program is designed to enhance Norwegian greenhouse gas inventory and to improve the evaluation of model-based estimates used for reporting land use and forestry under the United Nations Framework Convention on Climate Change (UNFCCC). Samples will be taken from all plots in the intensive grasslands category (approximately 300 sample plots) and a systematic selection of plots in forests (approx. 3000 sample plots). The main Soil Mission indicator is soil organic carbon stock or content.

Recently (in 2023) 'Norwegian soil monitoring program for soil health' (JordVAAK) was established. JordVAAK soil monitoring system will represent Norwegian **arable land**, i.e., cultivated soil, surface cultivated soil and infield pasture land. A range of indicators that describe the condition of the soil on the agricultural land will be assessed with special relevance to the soil erosion, loss of organic matter, loss of biodiversity, soil compaction and contamination identified as the main threats to Norwegian soils.

4.2.6 Identification of national differences and harmonization needs

<u>Soil monitoring systems</u>

A survey of PREPSOIL partners shows that soil monitoring programs differ significantly between countries. Of the 15 listed in the surveys, 3 monitoring schemes were dedicated to forest land (Spain, Norway, Poland), 6 to all types of use (Spain and France), and 6 to agricultural land (Norway, Poland, France, Denmark).

Most of these monitoring systems are carried out at national level, only in Spain there are three regional monitoring schemes dedicated to either single (desertification, erosion) or multiple (erosion, pollution, organic carbon loss, biodiversity loss, sealing) soil threats. From the survey carried out, it appears that different soil threats are taken into account in national monitoring systems, the most commonly monitored being: soil organic carbon loss, nutrient imbalance and soil contamination. Soil erosion and acidification were covered to a lesser extent, and only in single cases soil sealing (Spain) and loss of soil biodiversity (France). However, there is a lack of monitoring data on soil salinization or soil compaction. This may present some challenges in the context of implementing the requirements of the new Soil Monitoring and Resilience Directive (see chapter 4.3.3), in which all soil threats are included. Differences can also be found in the frequency of soil sampling, e.g. every 5 (Poland and France), 10 (Spain) or 12-15 years (France), as well as in the number (216, 820 and 2241 locations, in Poland, Denmark and France, respectively) and density of control points (from 10 m x 10 m to 16 km x 16 km). Samples are also taken from different depths, from either one (0-20 cm; Poland) or several (0-25, 25-50, 50-75, 75-100 cm; France and Denmark) depths. This appears to be in contradiction to the soil monitoring law, which calls for 0-20 cm sampling (similar to LUCAS) and soil health surveys every five years.

In some countries (France and Denmark), additional surveys on soil management are carried out during monitoring, e.g. crop rotation, soil tillage and fertilisation both organic and inorganic.

Soil indicators and threshold values

As each of the soil monitoring systems in operation has a different purpose and takes into account various forms of soil degradation, there are also discrepancies in the number and type of indicators analysed.

In general, it can be concluded that all Mission indicators were addressed in the national monitoring schemes, with the most common: soil organic carbon stock or content (France, Denmark, Poland, Norway), soil structure including bulk density (France and Denmark) and absence of erosion (Spain), soil nutrients and acidity (France, Poland, Norway) and soil pollutants (France, Poland, Spain, Norway). In contrast, landscape heterogeneity, forest cover and soil biodiversity were assessed least frequently, with biodiversity only included in one monitoring system (France), but at a very preliminary stage.

In some monitoring systems, additional indicators (to those listed above) are taken into account, such as available water capacity and exoenzymes activity (France), soil loss by erosion process (Spain) and soil water retention (Denmark).

It is worth highlighting that reference values are only available for some indicators, e.g. in Spain for soil erosion, in Poland for several pollutants (metals, PAHs, chloroorganic pesticides). In France, the threshold values proposed in the sludge regulation are used to assess metal concentrations. It was also highlighted that emerging pollutants addressed in the EU Soil Strategy (e.g. antimicrobials or PFAS compounds) are not included in the current soil monitoring. However, due to the specific methodological requirements, the inclusion of these pollutant groups in continuous monitoring can prove challenging.

Harmonization needs

Based on the results of Phase 2, a number of harmonisation needs can be identified:

- extending soil monitoring to non-agricultural uses; most monitoring concerns agricultural soils and while forest soils are present in the monitoring of several countries (Spain, Norway, Poland), information on urban and industrial soils is almost not available;

- harmonise the sampling protocol in terms of frequency of sampling, depth and grid of points to comply with the requirements of the Soil Monitoring and Resilience Directive;

- inclusion of a harmonised set of indicators in the national monitoring schemes; so far, indicators for biodiversity loss and soil sealing have been analysed to a limited extent;

- for most of the indicators analysed (listed above), the reference values necessary to determine soil health are missing;

- some MS indicated that better collaboration is needed between national system and LUCAS Soil monitoring.

4.3 Soil monitoring in Europe

4.3.1. LUCAS Soil monitoring for agricultural land

The Land Use/Land Cover Area frame statistical Survey Soil (LUCAS Soil) is an extensive and regular topsoil survey that is carried out across the European Union to derive policy-relevant statistics on the effect of land management on soil characteristics. It was initiated in 2006 to gather information on cover and land use, and since 2009 has been extended to include a soil component (Orgiazzi et al., 2018). Sampling is based on a regular 2 km × 2 km grid that covers the European territory, resulting in around 1 000 000 georeferenced sampling locations. Each point has been classified in accordance with seven land-cover classes using orthophotos or satellite images. From this overall pool, approximately 270 000 points are visited in the field by surveyors to assess the validity of the classification and to collect additional information that cannot be assessed remotely. Points were selected through a stratification process that provides coverage of all possible types of land cover and land use identified over the whole study area. Approximately 45 000 soil samples have been collected from several time-periods, 2009–2012, 2015, 2018 and 2022. The sampling design is based on the LUCAS campaign.
Analysis of the main properties of topsoil (0-20 cm) started in 2009 in 25 EU Member States. Approximately 20 000 topsoil samples were collected in the first sampling campaign and the LUCAS Soil was subsequently extended to Bulgaria and Romania in 2012 (generating around 2000 additional points). All samples were analysed for: percentage of coarse fragments, particle size distribution, pH, soil organic carbon, carbonates, total nitrogen, extractable nutrients, cation exchange capacity and multispectral properties. In 2012 LUCAS campaign,

trace elements were included. The 2018 edition also included: visual assessment of soil erosion, measurement of the thickness of the organic horizon in organic-rich soil, soil bulk density in 9000 locations and soil biodiversity (Bacteria and Archaea, Fungi, Eukaryotes, nematodes, arthropods, earthworms, metagenomics) in 1000 selected locations (Orgiazzi et al., 2018; Orgiazzi et ail., 2022). In addition, the pilot survey on residues of pesticides (3431 locations) and two antibiotics (600 locations) were conducted in 2018 (Jones et al., 2021; Orgiazzi et ail., 2022).

LUCAS Soil is dedicated to monitor agricultural land; however, some urban sites are included in the latest campaigns.

Some limitations of LUCAS soil monitoring can be identified: many parameters are measured on samples based on several modules that have been added over time. Ultimately, it covers most of the indicators available and pushed by science, but not always on all samples, but on part of them. The LUCAS Soil protocol is uniform across the EU, but there may have been changes in analytical methods between campaigns (e.g. for texture), which should be taken into account when using data from different campaigns.

4.3.2. EEA report

EEA report (EEA, 2023) synthesises current knowledge about key soil indicators in the light of current and new policies in support of healthy soils. The report considers the main soil threats: soil organic carbon loss, soil nutrients loss (N, P), soil acidification, soil pollution, soil biodiversity loss, soil erosion, soil compaction and soil sealing and provides in-depth discussion of indicators used to evaluate these threats. Based on the review of existing literature and databases, 12 soil quality indicators (Table 4.3.1) were selected in view of their appropriateness to assess soil degradation (unhealthy soils) related to various important soil functions or ecosystem services. It was assessed that for most cases, the selected indicators are well established, availability of data is acceptable at the European level and they are appropriate to describe key soil degradation types and impairment of key soil services.

Table 4.3.1. Indicators and thresholds recommended in the EEA report (2023) for agriculture and forest land.

Soil use	Indicator	Thresholds	Comment
Soil organic carbon loss			
Cropland	Falling below optimal SOC	Light soils: <1.2% SOC Medium soils: 1.2-1.9% SOC Heavy soils: >1.9% SOC	SOC: clay ratio: optimum SOC content as 10% of the clay content/vulnerability limit
Nutrient loss			

Agriculture	exceedance of critical levels of Nmin	NH_3 in air: 1-3 mg NH_3 m^{-3} NO_3 in ground water: 50 mg NO_3 L^{-1} N in surface water: 1.0-2.5 mg N L^{-1}	Mineral N: sum of available NH4 and NO3
Forest land	N limitation based on exceedance of C:N ratio	C:N 20-25 leakage from forests: 1 mg N L^{-1}	Forest floor organic layer
Agriculture	Falling below of optimal P	P concentration 25-35 (optimal P fertility class)	Extractable P concentration < optimum (value range refers to Mehlich 3-ICP; also available P-Bray P1 and Olsen P)
Forest land	P limitation based on exceedance of N:P ratio	N:P ratio > 18 (coniferous forests) N:P ration > 25 (deciduous forests)	Forest floor organic layer
		Soil acidification	
Agriculture	Exceedance of critical pH levels	1.pH < 4.5 – 4.7 (critical) 2.pH <5.0-5.5 (avoid)	1. Risk of Al toxicity 2. Limited availability of Ca, Mg, K and P
Forest land	Exceedance of critical inorganic Al levels	base cation:aluminium ratio =1 (0.5-2.0)	Base cations are Ca_2^+, Mg_2^+ and K^+
		Soil pollution	
All land uses	exceedance of screening values for critical risk from heavy metal and organic pollutants	Updated values for Cd, Cu, Pb and Zn (mg/kg): By country Database developed (Cd, Cu, Pb, Zn, As, Hg, Ni, Cr) Organic pollutants	Country-specific values vary broadly and are not necessarily comparable Stratification by land use and soil texture
		Soil erosion	
Agriculture	actual rate of soil loss by water erosion	2t/ha/year for shallow soils (<70cm depth) 4t/ha/year for deeper soils (≥70cm) (soil loss tolerance)	Soil formation rate: 0.3-1.4 t/ha/year Preliminary thresholds, derivation of site-adapted tolerable soil loss rates recommended The current indicator description includes only soil erosion by water, whereas the threshold addresses all other erosion types
		Soil biodiversity loss	
	loss of soil biodiversity (subindicators)	To be developed: Exceedance of safe minimum standards of ecosystem conservation Exceedance of operating ranges (OR) for specific soil animals and microorganisms	Requires sub-indicators by species and/ or (functional) group

Soil compaction			
	harmful subsoil compaction (subindicators)	Priority (sub)-indicators: Saturated hydraulic conductivity (Ks) <10cm/day Air capacity (AC) <5%	Exceedance of 'action values' Secondary sub-indicators with available thresholds: bulk density, internal soil strength, air permeability and oxygen diffusion
Soil sealing			
	sealed area per total land area	national targets to achieve 'No Net Land Take'	

Critical limits were also proposed for a set of indicators based on a risk-based approach, according to which soil degradation can be prevented if critical limits are not exceeded. It was stressed that the critical limits need to be further tested and validated taking into account regional specifications.

The report shows that existing systems for assessing soil degradation in Europe are not easily comparable and require harmonisation and additional research in this area. It was noted that the development of appropriate and widely applicable indicators and thresholds is hampered by the wide diversity of soils, biota and climate in Europe, as well as the diverse political, economic and social conditions determining priorities in this field. Therefore, it recommends that definitions of indicators, methods of analysis and sampling, and threshold values should be harmonized and agreed at the level of individual EU countries.

Soil monitoring in Europe faces the challenge of integrating different national and EU-wide soil surveys. In addition, different sampling systems may exist in different countries, for example between forest and agricultural soil monitoring, creating difficulties in comparison.

The main final recommendations from EEA report (EEA, 2023) for the future are as follows:

- available thresholds need to be validated (confirmed and/ or improved) and gaps in indicators and thresholds filled;
- a European protocol for soil sampling and analysis is needed;
- existing soil monitoring needs to be supported and improved as a tool to inform soil protection policies.

4.3.3. EU Soil Monitoring Law

The proposal for a new Soil Monitoring Law (Proposal for a Directive on Soil Monitoring and Resilience) was published on 5 July 2023 (European Commission, 2023) with the aim of protecting, restoring and ensuring the sustainable use of all soils in Europe. This document addresses all major soil threats, i.e. loss of soil organic carbon, erosion, salinization, compaction, nutrients imbalance, contamination, sealing, acidification and loss of soil biodiversity. The Soil Monitoring and Resilience' directive provides a framework for:

- monitoring and assessment of soil heath;
- sustainable soil management;

- identification, registration, investigation, assessment and management of contaminated sites.

Directive proposal defines several terms (including 'soil health') and establishes soil districts. In order to assess the state of the soil in relation to specific threats, a set of indicators has been proposed (Table 4.3.2) and, for some of them, criteria of healthy soil condition.

Table 4.3.2. Soil indicators proposed in the Soil Monitoring Law (European Commission, 2023)

<table>
<tr><th>Soil threat</th><th>Soil indicator</th><th>Criteria for healthy soil condition</th></tr>
<tr><td colspan="3">Criteria established at Union level</td></tr>
<tr><td>Salinisation</td><td>Electrical Conductivity
(deci-Siemens per meter)</td><td>< 4 dS m^{-1} when using saturated soil paste extract (eEC) measurement method, or equivalent criterion if using another measurement method</td></tr>
<tr><td>Soil erosion</td><td>Soil erosion rate
(tonnes per hectare per year)</td><td>≤ 2 t ha^{-1} y^{-1}</td></tr>
<tr><td>Loss of soil organic carbon</td><td>Soil Organic Carbon (SOC) concentration (g per kg) evaluated as a ratio SOC to Clay content</td><td>For mineral soils:
SOC/Clay ratio > 1/13</td></tr>
<tr><td>Subsoil compaction</td><td>Bulk density in subsoil
(upper part of B or E horizon)
(g per cm^3)</td><td><table>
<tr><td>Soil texture</td><td>range</td></tr>
<tr><td>sand, loamy sand, sandy loam, loam</td><td><1.80</td></tr>
<tr><td>Sandy clay loam, loam, clay loam, silt, silt loam</td><td><1.75</td></tr>
<tr><td>silt loam, silty clay loam</td><td><1.65</td></tr>
<tr><td>Sandy clay, silty clay, clay loam with 35-45% clay</td><td><1.58</td></tr>
<tr><td>Clay</td><td><1.47</td></tr>
</table></td></tr>
<tr><td colspan="3">Criteria established at Member States level</td></tr>
<tr><td>Excess nutrient content in soil</td><td>Extractable phosphorus
(mg per kg)</td><td>< "maximum value";
The "maximum value" shall be laid down by the Member State within the range 30-50 mg kg^{-1}</td></tr>
<tr><td>Soil contamination</td><td>Concentration of heavy metals in soil: As, Sb, Cd, Co, Cr (total), Cr (VI), Cu, Hg, Pb, Ni, Tl, V, Zn
(µg per kg)

Concentration of a selection of organic contaminants</td><td>Reasonable assurance, obtained from soil point sampling, identification and investigation of contaminated sites and any other relevant information, that no unacceptable risk for human health and the environment from soil contamination exists.</td></tr>
<tr><td>Reduction of soil capacity to retain water</td><td>Soil water holding capacity of the soil sample
(% of volume of water / volume of saturated soil)</td><td>The estimated value for the total water holding capacity of a soil district by river basin or subbasin is above the minimal threshold.</td></tr>
</table>

		The minimal threshold shall be set (in tonnes) by the Member State at soil district and river basin or subbasin level at such a value that the impacts of floodings following intense rain events or of periods of low soil moisture due to drought events are mitigated.
Soil indicators without criteria		
Excess nutrient content in soil	Nitrogen in soil (mg g^{-1})	No criteria
Acidification	Soil acidity (pH)	No criteria
Topsoil compaction	Bulk density in topsoil (A-horizon) (g cm^{-3})	No criteria
Loss of soil biodiversity	Soil basal respiration ((mm^3 O_2 g^{-1} hr^{-1}) in dry soil Member States may also select other optional soil descriptors for biodiversity such as: - metabarcoding of bacteria, fungi, protists and animals; - abundance and diversity of nematodes; - microbial biomass; - abundance and diversity of earthworms (in cropland); - invasive alien species and plant pests	No criteria
Land take and soil sealing	Total artificial land (km² and % of Member State surface) Land take, Reverse land take Net land take (average per year–- in km² and % of Member State surface) Soil sealing (total km² and % of Member State surface)	No critieria

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Van Egmond et al. 2021. Report on harmonized procedures for creation of databases and maps. EJP SOIL Deliverable 6.1. Report.
https://ejpsoil.eu/fileadmin/projects/ejpsoil/WP6/EJP_SOIL_D6.1_Report_on_harmonized_procedures_for_creation_of_databases_and_maps__final.pdf

Van Leeuwen et al. 2017. Gap assessment in current soil monitoring networks across Europe for measuring soil functions. *Environ. Res. Lett.,* 12 (2017) 124007, https://doi.org/10.1088/1748-9326/aa9c5c

Appendix 1 Detailed Template for the Phase 1

PREPSOIL TASK 5.1 – PHASE 1 (Template)

Introduction

One of the objectives of Task T5.1 is to ***review completed or ongoing EU projects in order to collect the available knowledge on soil monitoring and indicators across European projects, as well as to identify gaps and needs for harmonisation****. This corresponds to Phase 1 of task 5.1.*

For this review, a template (.doc file) was prepared to collect the most relevant information from each project (called here as a Project Brief).

Please answer in a comprehensive yet concise manner (up to 5-10 sentences in descriptive points); inserting a short table with the most important outputs of the project is also possible, if necessary.

In this phase, we do not intend to collect our opinions on soil monitoring, but only purely collect what the projects have reported. We intend to produce a several-page Project Brief (summary) for each project that will be used in the knowledge integration process and attached as an annex to the Deliverable 5.1.

Template for project review, V.3

I: Project ID and objective

Project details
Name and acronym:
Funding programme:
Countries involved:
Project duration *(start year and end year):*

Project main objective:
…..

II: Monitoring level considered *(please indicate appropriate from the list below)*

- field scale (or collection of test results requested by farmers or cooperatives and provided by soil testing laboratories)
- farm scale
- regional inside a country
- national
- European regional or transborder *(more than one country covered by soil monitoring)*

- European (*continental*)
- other scale (some km^2 scale, *e.g., in France sampling every 16 km for the RMQS programme (soil quality measurement network)*)

III: Indicators addressed in soil monitoring described in the project

Mission indicators *(please indicate relevant from the list below)*

- *Several of the Soil health indicators proposed by the Mission board 'Soil health and food' can be subdivided into sub-indicators.*
- presence of soil pollutants, excess nutrients and salts*; please indicate the specific group of pollutants*:
  - *trace elements,*
  - *organic pollutants (e.g., pesticides, PAHs, PFAS, etc.)*
  - *micro-plastics*
- soil organic carbon stock or content;
- soil structure including soil bulk density and absence of soil sealing and erosion;
- soil biodiversity; *please specify soil biodiversity indicators:*
  - *functional indicators (e.g., enzymatic activity, microbial biomass, microbial respiration)*
  - *structural indicators: microbial diversity (bacteria, fungi, archaea, viruses, algae); micro-meso-macrofauna (e.g., earthworms, ants, termites, millipedes, dung beetles, springtails)*
- soil nutrients and acidity (pH) *(essential nutrients: N, P, K, S, Ca; micronutrients)*;
- vegetation cover (*diversity of vegetation cover*);
- landscape heterogeneity *(farmland, forestry, urban green infrastructure, diversity of landscape elements)*;
- forest cover *(area of forests, area of wooded lands, share of non-native tree species)*

How soil health/quality indicators are estimated *(e.g., using only experimental characterizations, measurement and model (mention the model used); please specify the method used (e.g., pH water, pHCaCl$_2$ etc., CEC (Metson, Cobaltihexamine and others.), C (parallel or successive extractions, progressive combustion (RockEval), total combustion, spectroscopic methods), biodiversity (environmental DNA or traps))?*

Other indicators *(not listed above, e.g. land take indicator, soil artificial surface)* **describing soil health included in monitoring programmes** *(please specify)*:

Short summary of monitoring described in the project *(issues relevant for the monitoring harmonisation*)
Give all useful additional information if available:

- *the sampling procedure (it impacts variability and the need of replicates, and favour or not result harmonization)*
- *depth of soil considered,*
- *experimental procedure: number of samples per site or location, approximate mass of each sample and approximate distance between sampling points, homogenisation procedure (or not) in the laboratory,*
- *frequency of sampling.*

Is any soil health index proposed/developed?

IV: Was soil monitoring accompanied by any surveys on soil management?
carried out in parallel or at a different time to the soil sampling; details of its contents (is there access to this information or not)

V: Are any limit values (critical limits) (e.g. threshold values, reference values, relative change) used/proposed for soil health monitoring?

VI: Gaps and limitations in soil monitoring defined by the project

Gaps in soil monitoring
in terms of: sampling strategy (e.g. soil depth, sampling procedure); spatial resolution; type of threat monitored; land use; mission indicators (listed above), threshold/reference values

Major weaknesses/limitations in terms of soil monitoring harmonization

VII: Recommendations for future soil monitoring (*e.g. monitoring scheme and structure, indicators representing Soil Mission categories, measured and estimated indicators, accompanying non-soil indicators proposed*)

VIII: Existing approaches for monitoring of urban, industrial and natural areas, if considered.

IX: Additional information
(website, project coordinator, any other if relevant in your opinion)

Appendix 2 Brief descriptions of projects reviewed

Projects completed:

- SIREN
- LANDMARK
- iSQAPER
- EcoFinders
- Soil4EU
- RECARE
- URBAN SMS
- SIEUSOIL
- EEA report

Ongoing projects:

- EJP SOIL
- SERENA (EJP SOIL internal)
- MINOTAUR (EJP SOIL internal)
- STEROPES (EJP SOIL internal)
- HoliSoils
- LUCAS monitoring

Projects started in 2022/2023:

- ORCaSa
- BENCHMARKS
- AI4SOILHEALTH
- Carbon Farming CE
- IndiQuaSoils

SIREN - project brief

I: Project ID and objective

Project details	
Name and acronym:	Stocktaking for Agricultural Soil Quality and Ecosystem Services Indicators and their Reference Values (SIREN)
Funding programme:	Horizon 2020 – EJP Soil Internal
Countries involved:	Belgium, Switzerland, Czech Republic, Denmark, Estonia, Finland, France, Ireland, Italy, Latvia, Lithuania, The Netherlands, Norway, Poland, Portugal, Sweden, Slovenia, Slovakia, Spain, United Kingdom
Project duration *(start year and end year):*	02.2021-01.2022 (1 year)

Project main objective:
The EJP SOIL internal project SIREN aimed to identify and review national approaches to make use of soil data in the assessment of soil ecosystem services, and identified knowledge gaps and development needs that prevent policy implementation as experienced in the 20 countries participating in the SIREN consortium (Faber et al., 2022).

To fulfill the project objectives, the comprehensive conceptual framework linking soil quality to ecosystem services was implemented. Project member states were asked to fill a questionnaire to evaluate the way they use Soil Quality indicators to evaluate SES. In addition, to support the conceptual framework, a glossary of consistent terminology was created to define what is meant by: indicator, soil processes, soil functions, ecosystem approach, ecosystem services, nature's contributions to people (NCP), potential supply of ecosystem services, ecosystem service flow, ecosystem capacity, ecosystem health, soil quality and soil health, reference or reference value, target value, and natural capital.

SIREN produced a synthesis of policy-relevant soil quality indicators with high potential for harmonized application in national and European monitoring based on literature, international policy, international stakeholder opinions, wide application in national soil monitoring and EU projects contributing to **agricultural soil quality assessment**.

II: Monitoring level considered:

- regional inside a country
- national

As part of the SIREN project, an inventory of current knowledge on soil quality indicators was carried out in the project consortium countries. The information collected concerned the use of indicators at national and regional scales.

III: Indicators addressed in soil monitoring described in the project

Mission indicators:

- **presence of soil pollutants, excess nutrients** and salts*; please indicate the specific group of pollutants*:
  - ***trace elements,***
  - ***organic pollutants*** *(e.g., pesticides,* ***PAHs****, PFAS, etc.)*
- **soil organic carbon stock or content**;
- **soil structure**, **soil bulk density** and **erosion**;
- **soil biodiversity**; *please specify soil biodiversity indicators:*
  - ***functional indicators*** *(e.g., enzymatic activity, microbial biomass,* ***microbial respiration****)*
  - ***structural indicators****:* ***microbial diversity (bacteria, fungi, archaea, viruses, algae); micro-meso-macrofauna (e.g., earthworms, ants, termites, millipedes, dung beetles, springtails)***
- **soil nutrients and acidity (pH)** ***(essential nutrients: N, P, K, S, Ca; micronutrients)***;

No indicators were investigated, but many were included in the questionnaire and inventory activities of the SIREN project.

How soil health/quality indicators are estimated

SIREN made a stocktake of existing data sets (Faber et al. 2022)

Other indicators *(not listed above, e.g. land take indicator, soil artificial surface)* **describing soil health included in monitoring programmes** *(please specify)*:

Short summary of monitoring described in the project

SIREN made a stocktake of SQI indicators and their respective reference values and try to identify how SQI are used for soil ecosystem services assessment.

Is any soil health index proposed/developed?

IV: Was soil monitoring accompanied by any surveys on soil management?

V: Are any limit values (critical limits) (e.g. threshold values, reference values, relative change) used/proposed for soil health monitoring?

A stocktaking conducted in the SIREN included also limit values applied for the specific indicators among the EU member states.

VI: Gaps and limitations in soil monitoring defined by the project

Gaps in soil monitoring

Main gaps identified as a result of inventory of indicators used and monitored in the EU countries:

- The use of soil quality indicators in monitoring to assess soil functions and ecosystem services is not widely distributed across the participating EJP SOIL Member States.
- The largest commonality in indicators implemented by MS is the quantification of soil organic carbon (stocks and changes).
- There is omission in almost all countries in soil biological indicators, addressing soil biodiversity either with respect to structural aspects (species richness, etc.), or functional aspects (associated with soil functions and provision of services), *or both*.
- Indicators for water regulation and persistent organic contaminants are also scarcely implemented, whilst cost-effective methods have come available.

Major weaknesses/limitations in terms of soil monitoring harmonization

VII: Recommendations for future soil monitoring

- Develop 'Soil Health' concept in ecosystem health assessment
- Develop a tiered approach for the implementation of soil monitoring, and agree on a minimum indicator set for pan-European harmonisation; use indicators currently implemented by >50% of Member States as a preliminary Tier 1.
- Link and synchronise soil monitoring and ecosystem assessment
- Involve stakeholders in developing and implementing soil policy and management.
- Biological indicators are missing in most European countries but this is not due to the lack of importance of tracking, targeting and conserving soil biodiversity.

VIII: Existing approaches for monitoring of urban, industrial and natural areas, if considered.

Not considered in EJP SOIL as it deals with agricultural soil.

IX: Additional information

Website: https://ejpsoil.eu/soil-research/siren

Faber, J.H., Cousin, I., Meurer, K.H.E., Hendriks, C.M.J., Bispo, A., Viketoft, M., ten Damme, L., Montagne, D., Hanegraaf, M.C., Gillikin, A., Kuikman, P., Obiang-Ndong, G., Bengtsson J., Taylor A., 2022. Stocktaking for Agricultural Soil Quality and Ecosystem Services Indicators and their Reference Values. EJP SOIL Internal Project **SIREN Deliverable 2**, Report. Available at: https://ejpsoil.eu/fileadmin/projects/ejpsoil/1st_call_projects/SIREN/SIREN_D2_final_report.pdf

LANDMARK - project brief

I: Project ID and objective

Project details	
Name and acronym:	LAND Management: Assessment, Research, Knowledge base (LANDMARK)
Funding programme:	H2020
Countries involved:	The Netherlands, Denmark, Hungary, UK, Ireland, Belgium, France, Germany, Austria, France, China, Brazil, Switzerland, Romania, Sweden, Slovenia, Italy, Spain
Project duration *(start year and end year):*	2015 - 2019

Project main objective:

Comprehensively quantify the current and potential supply of soil functions across the EU, as determined by soil properties (soil diagnostic criteria), land use (arable, grassland, forestry) and soil management practices. One of specific objectives: development of a monitoring schema for the range of soil functions associated with different soil types, land-uses and European major climatic zones

II: Monitoring level considered:

- **farm scale**
- **European regional or transborder *(more than one country covered by soil monitoring)***
- **European (*continental*)**

III: Indicators addressed in soil monitoring described in the project

Mission indicators:

- **soil organic carbon stock or content**;
- **soil structure including soil bulk density and absence of soil sealing and erosion**;
- **soil biodiversity**; *please specify soil biodiversity indicators:*
  - ***functional indicators** (e.g., enzymatic activity, microbial biomass, microbial respiration)*
  - ***structural indicators**: microbial diversity (bacteria, fungi, archaea, viruses, algae); micro-meso-macrofauna (e.g., earthworms, ants, termites, millipedes, dung beetles, springtails)*
- **soil nutrients and acidity (pH) *(essential nutrients: N, P, K, S, Ca; micronutrients*)**;

How soil health/quality indicators are estimated?

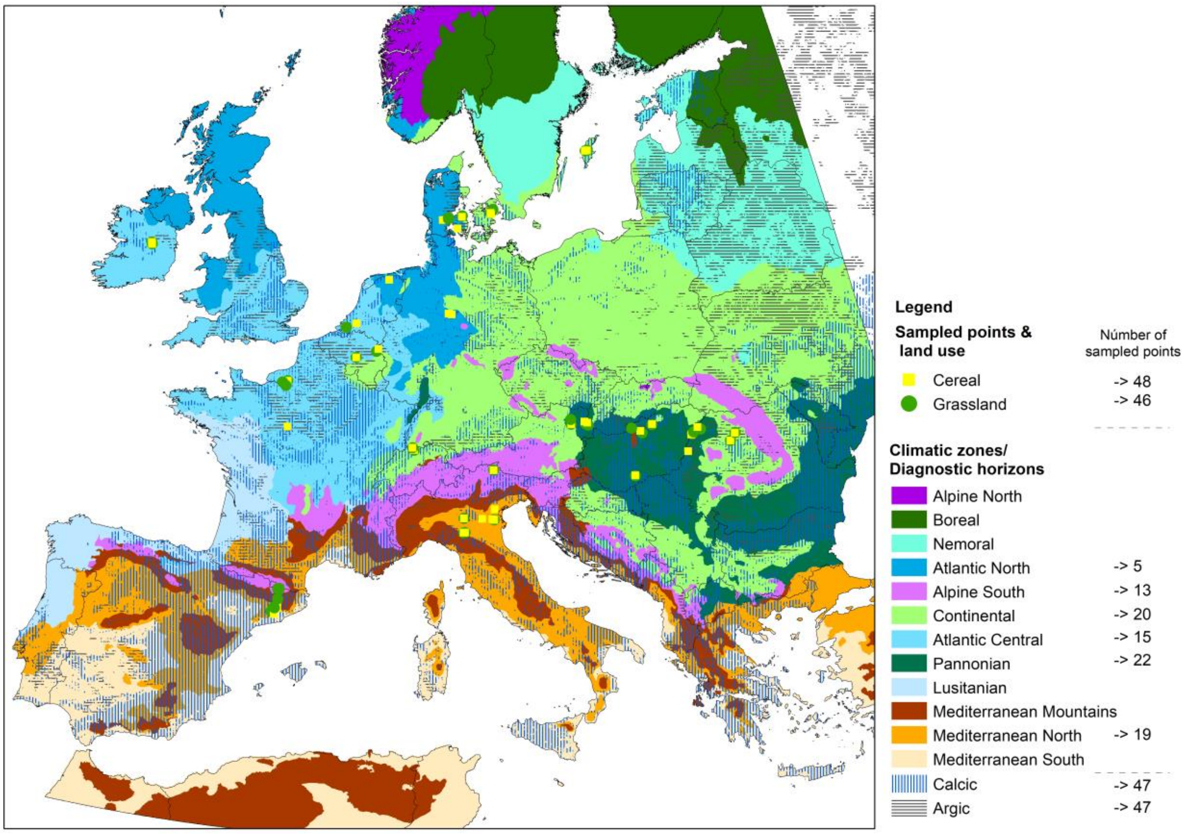
Soil indicators used to monitor soil functions are measured according to standard methods, directly after sampling and laboratory analysis. No detailed information on analytical protocols considered.

Other indicators *(not listed above, e.g. land take indicator, soil artificial surface)* **describing soil health included in monitoring programmes** *(please specify)*:
Attribute/SF:
Organic C/N/P/K, pH, Bulk density, C:N ratio, C mineralisation rate, Texture, Rooting depth, Microbial biomass, Drainage class, Soil temperature, Salinity, CEC, WHC, Groundwater table, Fe/Al, Earthworm community, Clay mineralogy, Soil slope, Bacterial community, Soil moisture, Microarthropod community, Fungal community, Top-layer infiltration capacity, Air-filled porosity, Field capacity days, Nematode community, Wilting points days, Enchytraeid community, Soil frost days, Redox state

Source: Van Leeuwen et al. 2017, https://doi.org/10.1088/1748-9326/aa9c5c

Short summary of monitoring described in the project
At one phase -the project evaluated existing sampling schemes, sample location distribution and frequency across 16 European countries, mainly dedicated to agricultural land.

At another phase LANDMARK focused on indicators that contribute to an assessment of soil functionality instead of threats. The regional indicators have been tested in Spring 2018 at 94 sites across Europe, based on soil types x land-use matrix for the major European climatic zones. LANDMARK utilised the Environmental Stratification of Europe in Environmental Zones by Metzger et al. (2005) and Jongman et al. (2006) as the basis for climatic zone selection. The following 6 climate zones have been identified for the testing and validation phase: Atlantic North, Atlantic Central, Continental, Alpine south, Mediterranean north and Pannonian (regional scale).



Source: https://landmarkproject.eu/pillars/monitoring-soil-quality-soil-functions-pillar2/

Is any soil health index proposed/developed?

No soil health index proposed but the project assessed which soil attributes can be used as potential indicators of five soil functions; (1) primary production, (2) water purification and regulation, (3) carbon sequestration and climate regulation, (4) soil biodiversity and habitat provisioning and (5) recycling of nutrients.

In total 33 attributes, selected by the Landmark consortium members were scored on relevance and sensitivity towards four integrated attributes (biology, nutrients, structure and hydrology) for each of the five soil functions.

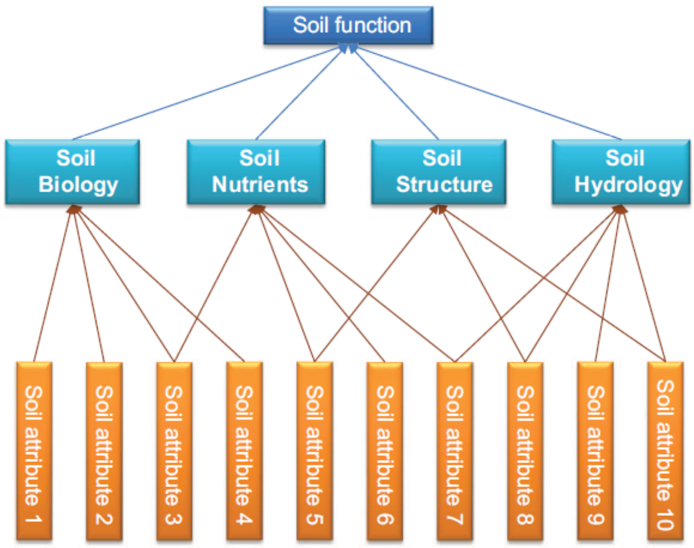


Figure 1. Diagram of conceptual model as framework for selecting attributes in the logical sieve method.

Source: Van Leeuwen et al. 2017, https://doi.org/10.1088/1748-9326/aa9c5c

IV: Was soil monitoring accompanied by any surveys on soil management?

No

V: Are any limit values (critical limits) (e.g. threshold values, reference values, relative change) used/proposed for soil health monitoring?

No

VI: Gaps and limitations in soil monitoring defined by the project

Gaps in soil monitoring

The project collected information on national soil monitoring programs in 16 countries.
Mainly weak representation of biological and physical parameters which limits capacity to monitor soil functions. Within physical attributes only soil texture showed a high sampling density.
Large variation between national programs in number of sites, site selection and included attributes, showing a clear lack of harmonisation between national approaches.

Major weaknesses/limitations in terms of soil monitoring harmonization

Analysing across Europe, current national soil monitoring form an unbalanced dataset, in which predominantly chemical soil parameters are included, but soil biological and physical attributes severely under represented. In addition, even when specific attributes, such as pH

or P content, were measured in several national monitoring programs, a wide range of different methods is being used, limiting the comparability.
A wide range of different methods is being used in the different soil monitoring programmes for measuring attributes relevant for soil functions.

VII: Recommendations for future soil monitoring

The LUCAS monitoring network is sufficiently dense for quantification of soil functions, but only if the sampling points are located homogenously and representatively throughout the biogeographical zones in the EU.
Harmonisation of soil sampling and range of analyses in the countries across Europe is therefore a key feature of a coordinated EU-wide soil monitoring.
The project proposes sets of soil parameters to be measured in order to monitor 2 soil functions.

VIII: Existing approaches for monitoring of urban, industrial and natural areas, if considered.

Not considered

IX: Additional information

Website: https://landmarkproject.eu/

iSQAPER - project brief

I: Project ID and objective

Project details	
Name and acronym:	Interactive Soil Quality Assessment in Europe and China (iSQAPER)
Funding programme:	H2020
Countries involved:	The Netherlands, Italy, Switzerland, Portugal, Spain, UK, Belgium, Poland, Estonia, Romania, Slovenia, Greece, China, Hungary, France
Project duration *(start year and end year):*	2015 - 2020

Project main objective:

The main aim of iSQAPER was to develop an interactive soil quality assessment tool (SQAPP) for agricultural land users that integrates process understanding and accounts for the impact of agricultural land use and management on soil properties, functions, and related ecosystem services. For this purpose, >30 long-term experimental field trials in the EU and China were analysed to derive regulating principles for integration in SQAPP. SQAPP was tested in 14 dedicated Case Study Sites in the EU and China covering a wide spectrum of farming systems and pedo-climatic zones. One of objectives was to derive and identify innovative soil quality indicators that can be integrated into an easy-to-use interactive soil quality assessment tool.

II: Monitoring level considered:

- **field scale**
- **farm scale**
- **regional inside a country**
- **national**
- **European regional or transborder** *(more than one country covered by soil monitoring)*
- **European (*continental*)**

III: Indicators addressed in soil monitoring described in the project

Mission indicators:

- **presence of soil pollutants, excess nutrients and salts*;* soil organic carbon stock or content;**
- **soil structure including soil bulk density and absence of soil sealing and erosion;**
- **soil biodiversity;**
    - *functional indicators (e.g., enzymatic activity, microbial biomass, microbial respiration)*

    - *structural indicators: microbial diversity (bacteria, fungi, archaea, viruses, algae); micro-meso-macrofauna (e.g., earthworms, ants, termites, millipedes, dung beetles, springtails)*
- **soil nutrients and acidity (pH)** ***(****essential nutrients: N, P, K, S, Ca; micronutrients)*;
- **vegetation cover (***diversity of vegetation cover, yield*);

How soil health/quality indicators are estimated?

Variety of standard methods. It is emphasized that choosing between substitute indicators would be beneficial.

Other indicators *(not listed above, e.g. land take indicator, soil artificial surface)* **describing soil health included in monitoring programmes** *(please specify)*:

Penetration resistance, spade diagnosis, ‘tea bag test’.
iSQAPER assessed the suitability of various novel soil quality parameters as soil quality indicators, studying their sensitivity to soil management and their relationship with traditional chemical (total organic carbon, pH, cation exchange capacity etc.), physical (water-stable aggregates, bulk density, water holding capacity etc.) and biological (microbial biomass C and N, soil respiration, etc.) soil parameters linked with soil functions.

Several soil parameters which hold promises in the delivery of simple, sensitive, and interpretable (also in terms of linkages with soil functions) soil quality indicators were selected:
• Labile organic carbon fractions: hydrophilic dissolved organic carbon (Hy), dissolved organic carbon (DOC), permanganate oxidizable carbon (POXC), hot water extractable carbon (HWEC), and particulate organic matter carbon (POMC);
• Soil general disease suppressiveness (measured as growth reduction upon pathogen addition) to Pythium ultimum;
• Nematode communities assessed with molecular methods (Illumina sequencing);
• Community level physiological profiling with MicroResp®, enzymatic activities and microbial community composition with phospholipid fatty acids (PLFA) (these parameters have been included in the framework of two Master thesis projects)

Short summary of monitoring described in the project

No specific soil monitoring was described. The project aimed at evaluating and recommending soil indicators assigned to soil functions and ecosystem services.

Is any soil health index proposed/developed?

No but soil indicators attributed to particular soil functions and ecosystem services are proposed.

IV: Was soil monitoring accompanied by any surveys on soil management?

The project emphasized importance of soil management data and other agricultural/climatic data for interpretation of results

V: Are any limit values (critical limits) (e.g. threshold values, reference values, relative change) used/proposed for soil health monitoring?

Not specifically explored – not a goal of the project

VI: Gaps and limitations in soil monitoring defined by the project

The objective of a given soil quality concept is often not clearly stated
Conceptually, linkages between indicators and soil functions or ecosystem services have sometimes been proposed but rarely established firmly, i.e. with experimental evidence. An asset of a novel soil quality framework would be such a firm linkage, and the possibility to choose indicators based on the targeted soil function or ecosystem service. Likewise, the possibility to choose between substitute indicators would be beneficial.

VII: Recommendations for future soil monitoring

Soil quality/health is not limited to the degree of soil pollution, but is commonly defined much more broadly as "The capacity of a soil to function within ecosystem and land-use boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health". Therefore, an important component of soil quality concepts is the identification of a set of sensitive indicators or attributes which reflect the capacity of a soil to fulfil its functions.
Importantly, the interpretation of the values of the proposed soil quality indicators needs to be well-defined. If no system for interpretation is provided, the concepts cannot be used in practice. For many soil properties, texture-dependent scoring curves need to be developed, which is possibly one of the greatest challenges of soil quality concepts.
The increased availability of digital soil maps and soil survey data such as the LUCAS soil data provides an opportunity to establish such scoring curves or target values.
The project provided review of soil quality indicators with respect to their sensitivity to indicate soil functions and soil threats and interactions with management as well as reliability

and simplicity of measurement. For example earthworm appears to be the most sensitive indicator for testing agricultural management practices.
Farmers often know very well which specific soil parameters are particularly relevant for their situation. Therefore in the future, view of land managers should be taken into account when evaluating various sets of indicators for soil quality. This would require a transdisciplinary and participatory approach.

VIII: Existing approaches for monitoring of urban, industrial and natural areas, if considered.

The project was dedicated to agricultural areas.

IX: Additional information

Website: www.isqaper-project.eu/

EcoFINDERS – project brief

I: Project ID and objective

Project details	
Name and acronym:	**Ecological Function and Biodiversity Indicators in European Soils EcoFINDERS**
Funding programme:	7 FP
Countries involved:	France, The Netherlands, Denmark, United Kingdom, Germany, Slovakia, Portugal, Belgium, Sweden, Slovenia, Ireland, Italy, China
Project duration *(start year and end year):*	2011-2014

Project main objective:
EcoFINDERS was a research project aimed at gaining knowledge about the biodiversity of soils in Europe and their associated ecosystem services. A first European-wide schema designed for monitoring soil biodiversity attributes. Samples were collected from forestry, arable, and grassland systems in five climatic zones of Europe in this pilot study. The project aimed to make progress in acquiring knowledge about soil biodiversity in Europe and its associated ecosystem services. Standard Operating Procedures (SOPs) for soil sampling and assessment of soil diversity and functions were developed. The results of the project contributed to raising awareness among policy makers, stakeholders and the general public on the value of soil biodiversity and soil functioning. The EcoFINDERS project represented a significant step forward in knowledge, know-how and awareness for policy makers and stakeholders.
The strategic aim of EcoFINDERS was to provide the EC with necessary tools to implement the Soil Thematic Strategy at EU level, including:

- Characterizing biodiversity of soil microorganism and soil fauna in European soil;
- Determining relationships between soil biodiversity-functions-ecosystem services;
- Assessing the impact of environmental parameters on soil biodiversity;
- Identifying indicators for monitoring soil biodiversity and activity.

II: Monitoring level considered *(please indicate appropriate from the list below)*

- national
- European regional or transborder *(more than one country covered by soil monitoring)*
- European (*continental*)

III: Indicators addressed in soil monitoring described in the project

Mission indicators

- ***soil organic carbon stock or content***;

- **soil structure including soil bulk density and absence of soil sealing and erosion;**
- **soil biodiversity**;
    - ***functional indicators (enzymatic activity, microbial biomass, microbial respiration)***
    - ***structural indicators****: microbial diversity (****bacteria, fungi****, archaea, viruses, algae);* ***micro-meso-macrofauna*** *fauna (protozoa, microarthropods, nematodes, oligochaeta), and their relation with above-ground biodiversity.*
- **soil nutrients and acidity (pH)** ***(essential nutrients: N, P, K, S, Ca; micronutrients****)*;
- **landscape heterogeneity** *(****farmland, forestry,*** *urban green infrastructure, diversity of landscape elements)*;
- **forest cover** *(****area of forests, area of wooded lands****,* ***share of non-native tree species****)*

How soil health/quality indicators are estimated
Biodiversity indicators was evaluated based on direct measurements of soil samples according to standard operating procedures developed and improved in the project.

Short summary of monitoring described in the project *(issues relevant for the monitoring harmonisation*)
Several standard operating procedures relating to sampling of soil organisms were developed or improved, and as a result the following ISO standards were modified: ISO 10381-6, ISO 10381-1, ISO 23611-1, ISO 23611-6, ISO 17155, ISO 11063, ISO 29843-2, ISO/CD 18311, ISO 17601.

VI: Gaps and limitations in soil monitoring defined by the project

Gaps in soil monitoring
A lack of standardization of the methods and procedures used for assessment of many soil biodiversity indicators was identified in the course of project implementation. In cooperation with International Organization for Standardization (ISO), TC 190 'Soil Quality' a list of standards, which needed improvement (based on knowledge and project results) was established. As a result, the range of ISO standards relating to soil microorganisms and soil fauna was modified.

Major weaknesses/limitations in terms of soil monitoring harmonization

VII: Recommendations for future soil monitoring

Recommendations according to Griffiths et al., 2016:
- For a large-scale biological indicator programme standardisation of methods is an absolute necessity, otherwise it is not possible to properly compare results;
- It would also necessitate accurate prescription of sampling appropriate for the land uses and edaphic conditions within the monitoring area.

- A suite of complementary indicators is necessary, ideally linking biodiversity to soil functioning.
- The ongoing developments in nucleic acid based analyses of biodiversity are likely to improve the throughput and resolution of biodiversity indicators, which need to cover both microbial and faunal groups.
- Indicators for ecosystem functions related to the services of water regulation, C-sequestration and nutrient pro-vision would include a minimum suite of: earthworms; microbial functional genes; and bait lamina.

VIII: Existing approaches for monitoring of urban, industrial and natural areas, if considered.

IX: Additional information

Website: https://projects.au.dk/ecofinders//
https://ect.de/ecofinders/

Result of the EcoFINDERS project were published in several deliverables and papers, e.g.:

Orgiazzi A., Panagos P., Yigini Y., Dunbar M.B., Gardi C., Montanarella L., Ballabio C. 2016. A knowledge-base approach to estimating the magnitude and spatial patterns of potential threats to soil biodiversity. Science of the Total Environment, 545-546, 11-20, https://doi.org/10.1016/j.scitotenv.2015.12.092

Römbke J., Winding A. 2014. Deliverable D6.4 Publication of drafts of ISO standards and OECD guidelines of the selected recommended indicators.

Griffiths B.S. et al. 2016. Selecting cost effective and policy-relevant biological indicators for European monitoring of soil biodiversity and ecosystem function. Ecological indicators, 69, 213-223.

Soil4EU - project brief

I: Project ID and objective

Project details	
Name and acronym:	**Providing support in relation to the implementation of the EU Soil Thematic Strategy (Soil for EU)**
Funding programme:	Service/contract to DG-ENV
Countries involved:	Project partners: The Netherlands, Germany, Spain, Poland. Scope: EU
Project duration *(start year and end year)*:	2016-2019

Project main objective:

The goal of the service was to support of DG ENV's obligations and activities in the context of the implementation of non-legislative pillars of the Soil thematic Strategy and support to the implementation of the European Soil Partnership, i.e. related to continued awareness raising, improved integration of soil protection into existing policy instruments, and the integration of soil-related Ecosystem Services into policy instruments.

II: Monitoring level considered *(please indicate appropriate from the list below)*

- field scale
- farm scale
- regional inside a country
- national
- European regional or transborder *(more than one country covered by soil monitoring)*
- European (*continental*)

III: Indicators addressed in soil monitoring described in the project

Mission indicators

- **presence of soil pollutants**,
- **soil organic carbon stock or content;**
- **soil structure** including soil bulk density and absence of soil sealing and erosion;
- **soil biodiversity**;
- **soil nutrients and acidity** (pH) *(essential nutrients: N, P, K, S, Ca; micronutrients)*;
- **landscape heterogeneity** *(farmland, forestry, urban green infrastructure, diversity of landscape elements)*;

How soil health/quality indicators are estimated

Not explored in detail.

Short summary of monitoring described in the project *(issues relevant for the monitoring harmonisation*)

Report 1.5 delivers overview of soil monitoring programmes/networks across European countries.

VI: Gaps and limitations in soil monitoring defined by the project

Historical soil data are available in almost all the Member States. However, this does not mean that the soil data is necessarily collected in an organized way or consistently stored in one (national) database or information system that is easily accessible. In other words, soil data are sometimes not collected or only in a primary state, sometimes available but not usable, and sometimes not shared.

A heterogeneous national systems for the study of soils in the EU in the past century resulted in difficulties for the homogenization of available national maps and related soil data. Additionally, a number of European countries have not yet systematically produced sufficiently detailed soils maps, or do not have an active organization in charge of such tasks.

The provision of permanently available quality-proven data (scenarios) and technologies are crucial for land users, planners and decision makers. Limitations in harmonized soil data throughout the EU have hampered the adoption of soil protection policy instruments. That is one of the reasons why data, data availability and harmonisation are most relevant also for the trans-boundary dimension of soil degradation.
Computational modelling has proven to be a key tool for integrated assessments and mitigation strategies in the field of soil erosion. Research also emphasizes the remaining gaps in knowledge about soil processes and that new approaches to modelling are needed.

Financing soil monitoring under the current situation where soil issues/responsibilities and soil information are scattered among different administrative services and research institutions and disciplines. The financial resources are thus scattered and respond to different objectives depending on which administration is supporting the information system.

VII: Recommendations for future soil monitoring

Social and economic data is required in order to assess the specific impacts (extent and costs) due to a transboundary caused loss of soil functions and the related decline of ecosystem services due to cross-border soil degradation. Such an assessment is needed as a basis for the provision of new and comparable data in order to understand and quantify drivers and impacts of soil degradation and, based on such evidence, to inform practical and policy response.

Data generation and processing requires calibrated methods for data acquisition and evaluation. In some member states, no coherent data collection methods exist. This increases the complexity of data comparability across national borders. A start has to be made at local/regional level on data and information on impacts, and then go up in scale (national/EU/global).

Pressures on soils can be quantified with the use of models together with the support of monitoring systems but it requires harmonized data, an example is data on contaminated sites, on national as well as on EU-level. Moreover, standards and protocols for data in support of vulnerability and risk assessments, and decision-support systems need to be established.

It was recommended to solve the problem of privacy and personal data protection laws on the publication of georeferenced soil data and to provide common and clear data access and data protection standards.

VIII: Existing approaches for monitoring of urban, industrial and natural areas, if considered.

No specific soil monitoring programs are elaborated but the project emphasised the role of using soil information (mainly spatial) in spatial planning and urban development. Good practice examples are listed.

IX: Additional information

https://www.deltares.nl/en/expertise/projects/soils4eu-importance-soils-societal-challenges-europe

RECARE - project brief

I: Project ID and objective

Project details	
Name and acronym:	Preventing and Remediating degradation of soils in Europe through Land Care (RECARE)
Funding programme:	FP7
Countries involved:	The Netherlands, Greece, Denmark, Spain, Cyprus, Norway, Portugal, Iceland, Switzerland, Austria, Belgium, Germany, UK, Sweden, Slovakia, Romania, Poland, Italy,
Project duration *(start year and end year):*	2013 - 2018

Project main objective:

The main aim of RECARE was to develop effective prevention, remediation and restoration measures using an innovative trans-disciplinary approach, actively integrating and advancing knowledge of stakeholders and scientists in 17 Case Studies, covering a range of soil threats in different bio-physical and socio-economic environments across Europe.
The activities led to reaching the following objectives through involving Case Study sites, i) the current state of degradation and conservation assessed using a new methodology, based on the WOCAT mapping procedure, ii) impacts of degradation and conservation on soil functions and ecosystem services quantified in a harmonized, spatially explicit way, accounting for costs and benefits, and possible trade-offs, iii) prevention, remediation and restoration measures selected and implemented by stakeholders in a participatory process evaluated regarding efficacy, and iv) the applicability and impact of these measures at the European level assessed using a new integrated bio-physical and socio-economic model, accounting for land use dynamics as a result of for instance economic development and policies.

II: Monitoring level considered *(please indicate appropriate from the list below)*

- field scale
- farm scale
- regional inside a country
- national
- European regional or transborder *(more than one country covered by soil monitoring)*
- European (*continental*)

III: Indicators addressed in soil monitoring described in the project

Mission indicators

- **presence of soil pollutants**,
- **soil organic carbon stock or content;**
- **soil structure** including soil bulk density and absence of soil sealing and erosion;
- **soil biodiversity**;
- **soil nutrients and acidity** (pH) *(essential nutrients: N, P, K, S, Ca; micronutrients)*;
- **vegetation cover** (diversity of vegetation cover);
- **landscape heterogeneity** *(farmland, forestry, urban green infrastructure, diversity of landscape elements)*;

How soil health/quality indicators are estimated

No overall soil health index proposed. For a range of soil threats th eindocators ilisted and described in the report: 'Soil threats in Europe. Status, methods, drivers and effects on ecosystem services', Stolte et al. 2016.
https://esdac.jrc.ec.europa.eu/public_path/shared_folder/doc_pub/EUR27607.pdf

Other indicators

Soil sealing/land take indicators (sealing rate/transition index of high quality soils), soil temperature, ancillary weather indicators, plant rooting.

Short summary of monitoring described in the project *(issues relevant for the monitoring harmonisation*)

One of the reports (D6.1) was aimed at developing harmonized field monitoring strategy for assessing the effectiveness of the selected soil prevention, remediation, and restoration measures. The approach was therefore rather focused on monitoring effects of soil management practices against threats to soil. The list of soil indicators was developed, assigned to particular threats to soil, to be measured in order to test soil management effects.

VI: Gaps and limitations in soil monitoring defined by the project

No regulations that clearly and coherently define indicators for monitoring and evaluating the necessity of remedial measures.

VII: Recommendations for future soil monitoring

Improved monitoring is required of policy impacts by developing or improving robustness of spatial data, to evaluate how public money is being spent and the impact of that spending. Incentives are needed for authorities to collect data. This can also be done through specific pilot cases for monitoring.
Integrated assessment, integrating also economic assessment, of impacts of soil management measures on multiple objectives, including biodiversity, soil protection, measures, climate change mitigation and adaption, water.
Concerning soil contamination: define guidelines, screening values and thresholds that trigger investigation of potentially contaminated sites; standardise definitions, methods of sampling and monitoring indicators, as well as develop a common language and comparability of information; define monitoring requirements to measure progress. This common framework for historical soil contamination needs to be placed within a set of coherent EU rules that define the role of soil, targets and priorities on soil contamination.6 Without such a framework, there is limited ability to integrate soil contamination concerns in wider policies, including EU funding instruments, as well as limited incentive to act in countries where there is a lack of political will to address soil protection in a coordinated way.

VIII: Existing approaches for monitoring of urban, industrial and natural areas, if considered.

The monitoring approach tested in one of the Case Studies (soil sealing case study) involved classification of land use changes within time series to spatially evaluate soil sealing/land take rate. Combination of spatial land use change data with spatial soil information, for example on soil texture or soil production potential, enabled calculation of ‘transition index of high quality soils’. Such the indicators inform whether a given soil class is urbanized preferentially.

IX: Additional information

http://www.envista.it/archive/recare-hub.eu/index.html

URBAN SMS - project brief

I: Project ID and objective

Project details	
Name and acronym:	Urban Soil Management Strategy (URBAN - SMS)
Funding programme:	Central Europe
Countries involved:	Germany, Slovenia, Italy, Austria, Poland, Slovakia, Czech Rep.
Project duration *(start year and end year):*	2008 - 2013

Project main objective:
URBAN SMS was aimed to develop soil management strategy for municipalities to consider the value of soils and their different functions within the urban planning process. The project was based on a range of key elements: the Municipal soil manager that acts as frame on which organizational level soil management should be included in urban planning procedure and gives options how goals, strategies and tools may interact. Second key element of the project were technical tools for including soil aspects in urban planning. A software suite was developed consisting of a desktop and a web solution each containing 8 different soil evaluation tools. The tools were tested in pilot areas. Last key element was raising the awareness of all stakeholders as well as to general public to the importance of soil in urban areas. Materials promoting this issue were produced and collected in an "Awareness raising package".

II: Monitoring level considered *(please indicate appropriate from the list below)*

- **field scale**
- **farm scale**
- **regional inside a country**
- **national**

III: Indicators addressed in soil monitoring described in the project

Mission indicators

- **presence of soil pollutants**, excess nutrients and salts; *please indicate the specific group of pollutants*:
  - *trace elements,*
  - *organic pollutants (e.g., pesticides, PAHs, PFAS, etc.)*
- **soil organic carbon stock or content**;
- **soil structure including soil bulk density and absence of soil sealing and erosion**;
- **soil nutrients and acidity (pH)** *(essential nutrients: N, P, K, S, Ca; micronutrients)*;
- **vegetation cover** (*diversity of vegetation cover*);

- **landscape heterogeneity** *(farmland, forestry, urban green infrastructure, diversity of landscape elements)*;
- **forest cover** *(area of forests, area of wooded lands, share of non-native tree species)*

How soil health/quality indicators are estimated

Standard methods for chemical parameters. The project did not deal with unifying analytical protocols. Landscape, vegetation and forest indicators based on available spatial information.

Short summary of monitoring described in the project *(issues relevant for the monitoring harmonisation*)
The project fully dedicated to urban and suburban soils. Please see section XII of the brief.

VI: Gaps and limitations in soil monitoring defined by the project

Regular monitoring and evaluation are needed in urban soil management. Better monitoring system or evaluation of open space and soil loss in the city as a basis for further strategic decisions of the politicians is needed (for example as part of a status report). Indicators of sustainability and related thresholds should be defined.

VII: Recommendations for future soil monitoring

The use of thresholds to protect soil has to be combined with an efficient monitoring system. Only if it is possible to monitor the quality of soil, any instrument linked with thresholds can be used efficiently. In urban development all decisions need to be based on existing soil data as much as possible, but monitoring of soil serves the necessity to know about future soil conditions. An evaluation can validate these monitoring assumptions and therefore indicators for the impacts on soil quality in urban development can be developed and applied in future planning decisions.

VIII: Existing approaches for monitoring of urban, industrial and natural areas, if considered.

The project provided the pilot monitoring approach tested in Case Studies across Central Europe cities. The approach involved classification of land use changes within time series to spatially evaluate soil sealing/land take rate. Combination of spatial land use change data with spatial soil information, for example on soil texture or soil production potential, enabled calculation of ‘transition index of high quality soils’.

IX: Additional information
https://keep.eu/projects/5537/Urban-Soil-Management-Strate-EN/

SIEUSOIL - project brief

I: Project ID and objective

Project details	
Name and acronym:	Sino-EU Soil Observatory for Intelligent Land Use Management (SIEUSOIL)
Funding programme:	H2020
Countries involved:	EU (Greece, Czech Republic, Belgium, Austria, Spain, Latvia, Portugal, Poland, Hungary) and China
Project duration *(start year and end year):*	2019-2022

Project main objective:
Climate change impacted agriculture and ecosystems, posing a threat to the sustainable management of soil. Improving soil quality to maximize land productivity while minimizing environmental impacts was a key requirement for sustainable agricultural production. The EU-funded SIEUSOIL project was a joint effort between the EU and China to study ways for the prudent use of soil and propose adequate practices for soil management. The project aimed to create and develop an EU-China Web Observatory platform that would offer open linked data on soil condition and potential threats. It was also intended to support sustainable and wise soil management based on advanced technologies to increase productivity, reduce environmental footprints, and assist policymaking processes.

II: Monitoring level considered:

- field scale (or collection of test results requested by farmers or cooperatives and provided by soil testing laboratories)
- farm scale
- regional inside a country
- national
- European regional or transborder *(more than one country covered by soil monitoring)*
- European (*continental*)

III: Indicators addressed in soil monitoring described in the project

Mission indicators:
- **presence of soil pollutants, excess nutrients and salts*;***
- **soil structure including soil bulk density and absence of soil sealing and erosion;**
- **soil biodiversity; *please specify soil biodiversity indicators:***
  - ***functional indicators (e.g., enzymatic activity, microbial biomass, microbial respiration)***
  - ***structural indicators: microbial diversity (bacteria, fungi, archaea, viruses, algae); micro-meso-macrofauna (e.g., earthworms, ants, termites, millipedes, dung beetles, springtails)***

- **soil nutrients and acidity (pH)** ***(essential nutrients: N, P, K, S, Ca; micronutrients)*****;**
- **vegetation cover (*****diversity of vegetation cover*****);**
- **landscape heterogeneity** ***(farmland, forestry, urban green infrastructure, diversity of landscape elements)*****.**

How soil health/quality indicators are estimated
The Remote Sensing and in situ online monitoring was done.

Other indicators *(not listed above, e.g. land take indicator, soil artificial surface)* **describing soil health included in monitoring programmes** *(please specify)*:

Short summary of monitoring described in the project

- The monitoring combine Remote Sensing and in situ online monitoring

Is any soil health index proposed/developed?
no

IV: Was soil monitoring accompanied by any surveys on soil management?
yes, focus was on precision farming methods

V: Are any limit values (critical limits) (e.g. threshold values, reference values, relative change) used/proposed for soil health monitoring?

no

VI: Gaps and limitations in soil monitoring defined by the project

Gaps in soil monitoring
monitoring was mainly focused on field monitoring for precision farming

Major weaknesses/limitations in terms of soil monitoring harmonization
We focused on GLOSIS model

VII: Recommendations for future soil monitoring
no

VIII: Existing approaches for monitoring of urban, industrial and natural areas, if considered.
n/A

IX: Additional information
Website: https://www.sieusoil.eu/

EEA report - report brief

I: Project ID and objective

Project details	
Name and acronym:	Soil monitoring in Europe. Indicators and thresholds for soil health assessments
Funding programme:	European Environmental Agency
Countries involved:	
Project duration *(start year and end year):*	report completed and published 2023

Report main objective:
This report synthesises current knowledge about key soil indicators in the light of current and new policies in support of healthy soils. The report considers the 8 main soil threats (soil organic carbon loss, soil nutrients loss (N, P), soil acidification, soil pollution, soil biodiversity loss, soil erosion, soil compaction and soil sealing) listed in the EU Soil Thematic Strategy. The impact of each threat on key soil ecosystem services as well as appropriateness of indicators for assessing the condition, degradation, resilience and valuable services of soil was described. In addition, the report compiles relevant information on indicator threshold values and proposes a conceptual framework for assessing soil degradation based on the assumption that exceeding an indicator threshold value triggers action.

II: Monitoring level considered:

- national
- European

In this report current knowledge on indicators were reviewed based in the context of possibility to applied uniform indicators and their values across all EU countries.

III: Indicators addressed in soil monitoring described in the project

Mission indicators:

- **presence of soil pollutants**, **excess nutrients**; *please indicate the specific group of pollutants*:
    - ***trace elements,***
- **soil organic carbon content**;
- **sealing and erosion**;
- **soil biodiversity**
- **soil nutrients and acidity (pH)** ***(essential nutrients: N, P***);

Based on the review of existing literature, databases, report 12 soil quality indicators (Table below) were selected in view of their appropriateness to assess soil degradation (unhealthy soils) related to various important soil functions or ecosystem services. It was assessed that for most cases, the selected indicators are well established, availability of data is acceptable at the European level and they are appropriate to describe key soil degradation types and impairment of key soil services. With a healthy, undegraded soil, in full capacity of its expected functions, none of the thresholds for these indicators would be exceeded.

Some indicators overviewed in this report covers Mission indicators mentioned above.

Table 0-1 Overview of soil threat indicators investigated in EEA report

Table 10-1: Overview of soil threat indicators investigated in this report

Note: The current knowledge base covers a limited set of land uses and soil properties, for which thresholds are available; in the future, all relevant land uses and sites need to be covered.

Soil threat	Indicator	Thresholds	Comment
Soil organic carbon loss			
Cropland	Falling below optimal SOC	Light: < 1.2 [% SOC] Medium: 1.2-1.9 Heavy: > 1.9	SOC/Clay ratio (Johannes et al., 2017) optimum SOC content as 10% of the clay content/vulnerability limit
Nutrients loss			
Agriculture	Exceedance of critical levels of mineral nitrogen (agricultural land)	NH_3 in air: 1 – 3 [mg NH_3 m^{-3}] NO_3 in ground water: 50 [mg NO_3 l^{-1}] N in surface water: 1.0 to 2.5 [mg N l^{-1}]	Mineral N: sum of available NH_4 and NO_3
Forest land	N limitation based on exceedance of C/N ratio	C/N 20-25 leakage from forests: 1 [mg N l^{-1}]	Forest floor organic layer
Agriculture	Falling below of optimal phosphorus	P concentration 25-35 (optimal P fertility class)	Extractable P concentration < optimum (value range refers to Mehlich 3-ICP; also available: P-Bray P1 and Olsen P)
Forest land	P limitation based on exceedance of N/P ratio	N/P ratio > 18 (coniferous forests) N/P ratio > 25 (deciduous forests)	Forest floor organic layer
Acidification			
Agriculture	Exceedance of critical pH levels	1. pH < **4.5** - 4.7 (critical) 2. pH < **5.0** - 5.5 (avoid)	1. Risk of Al toxicity 2. Limited availability of Ca, Mg, K and P
Forest land	Exceedance of critical inorganic Al levels	base cation (Bc)/aluminium ratio = 1 (0.5-2.0)	Bc = Ca+Mg+K
Soil pollution			
All land uses	Exceedance of screening values for critical risk from heavy metals and organic pollutants	Updated values for Cd, Cu, Pb and Zn [mg/kg] in this report - by country - data base developed (Cd, Cu, Pb, Zn, As, Hg, Ni, Cr) - organic pollutants:	Country-specific values vary broadly and are not necessarily comparable Stratification by land use and soil texture
Soil erosion			
Agriculture	Exceedance of actual rate of soil loss by water erosion	2 [t ha-1 yr-1] for shallow soils (< 70 cm depth) 4 [t ha-1 yr-1] for deeper soils (>= 70 cm)*) (soil loss tolerance)	Soil formation rate: 0.3 to 1.4 t/ha/yr (Verheijen et al. 2009) Preliminary thresholds, derivation of site-adapted tolerable soil loss rates recommended The current indicator description in this report only includes soil erosion by water, whereas the threshold addresses all other erosion types.
Soil biodiversity loss			
	Loss of soil biodiversity (subindicators)	to be developed: (a) Exceedance of safe minimum standards of ecosystem conservation	Requires sub-indicators by species and/or(functional) group

		(b) exceedance of operating ranges (OR) for specific soil animals and microorganisms	
Soil compaction			
	Harmful subsoil compaction (subindicators)	Priority (sub) indicators: Saturated hydraulic conductivity (Ks) < 10 [cm/d] Air capacity (AC) < 5 [%]	Exceedance of "action values" (Zink et al. 2011) Secondary subindicators with available thresholds: bulk density, internal soil strength, air permeability and oxygen diffusion
Soil sealing			
	Sealed area per land total area	National targets to achieve No Net Land Take	

*) Loss rates lower than 2 t/ha/yr shall be mandatory on soils adjacent to water bodies, and/or soils with elevated levels of pollutants; such lower limits are needed to maintain water quality.

IV: Was soil monitoring accompanied by any surveys on soil management?

Not relevant

V: Are any limit values (critical limits) (e.g. threshold values, reference values, relative change) used/proposed for soil health monitoring?

Critical limits have been proposed for a set of indicators for assessing whether soil is degraded or not. The risk-based approach has been extended to soil indicators (soil hazards) other than pollution. According to this approach, soil degradation can be prevented if critical limits are not exceeded. It was emphasised that critical limits must be further tested and validated taking into account regional specifications.

VI: Gaps and limitations in soil monitoring defined by the project

Gaps in soil monitoring

The report shows that the existing systems for assessing soil degradation in Europe are not easily comparable and require harmonisation and additional research in this field.

Major weaknesses/limitations in terms of soil monitoring harmonization

VII: Recommendations for future soil monitoring

It was recommended that definitions of indicators, methods of analysis and sampling and threshold values be harmonised and agreed at the level of individual EU countries.

The authors recommend for the future:

- the filling of remaining gaps (e.g., indicators for water storage, soil biological indicators, wind erosion);
- Available thresholds need to be validated (confirmed and/ or improved) and gaps in indicators and thresholds filled.
- representativity of indicators and thresholds by land use (since existing threshold do not cover all land use types);

- the development of a European soil indicator system (including a protocol for soil sampling and analysis) based on the analysis of policy needs and experience from existing soil monitoring;
- the refinement of the soil threat approach through soil functional indicators and site- and land-use specific critical limits.

VIII: Existing approaches for monitoring of urban, industrial and natural areas, if considered.

All types use (agricultural, forest, etc.)

IX: Additional information

Website: https://www.eea.europa.eu/publications/soil-monitoring-in-europe

EJP SOIL - project brief

I: Project ID and objective

Project details	
Name and acronym:	EJP SOIL
Funding programme:	Horizon 2020
Countries involved:	The EJP SOIL consortium consists of 26 partners from 24 countries ensuring a large representation of European countries.
Project duration *(start year and end year)*:	2020-2025

Project main objective:
The overall goal of the EJP SOIL programme is to build a sustainable European integrated research system and develop and deploy a reference framework on climate-smart, sustainable agricultural soil management. Within EJP SOIL WP6 focusses on data management, monitoring soils and mapping soil information.

II: Monitoring level considered:

- **field scale**
- **regional inside a country**
- **national**
- **European** (*continental*)

Several scales are investigated depending on the WP (e.g.WP6) or projects.

III: Indicators addressed in soil monitoring described in the project

Mission indicators:

- **presence of soil pollutants, excess nutrients and salts**
- **soil organic carbon stock or content;**
- **soil structure including soil bulk density and absence of soil sealing and erosion;**
- **soil biodiversity**;
- **soil nutrients and acidity (pH)**

Several indicators are investigated depending on the WP (e.g.WP6) or projects, including contaminants even if it not the main purpose of EJP SOIL.

How soil health/quality indicators are estimated
Depending on the WP (e.g.WP6) or projects several data are used based on measurements made in the projects. WP6 and WP2 made a stocktake of existing datasets and respective methods used (see for example Deliverable D2.2, D6.1 and D6.3).

Other indicators *(not listed above, e.g. land take indicator, soil artificial surface)* **describing soil health included in monitoring programmes** *(please specify)*:

Short summary of monitoring described in the project
WP6 made a stocktake (see Deliverable 6.3) to describe the monitoring networks in EU (mainly EJP SOIL countries). This description is currently being published and includes the description of the sampling strategy and procedure, the methods used in field and at lab to prepare and analyse the samples.

Is any soil health index proposed/developed?
Not yet

IV: Was soil monitoring accompanied by any surveys on soil management?

It depends on the WP and projects financed. WP6 made a stocktake (see Deliverable 6.3) to describe the monitoring networks in EU (mainly EJP SOIL countries). This description is currently being published and includes the metadata collected (e.g. management practices, land uses, land cover, elevation…).

V: Are any limit values (critical limits) (e.g. threshold values, reference values, relative change) used/proposed for soil health monitoring?

WP6 is running a stocktake on indicators and threshold values (Deliverable 6.5 to be submitted in September 2023) across EJP SOIL partners. This will complete what was already done within WP2, SIREN and SERENA projects.

VI: Gaps and limitations in soil monitoring defined by the project

Gaps in soil monitoring
When analysing the stocktake made within EJP SOIL WP6 on soil monitoring network across EJP SOIL partners, the following gaps were identified:

- some countries only sample the top soil (e.g. 0-10 cm) / few countries sample under 0.5 m
- organic contaminants and soil communities (i.e. soil biodiversity) are poorly monitored compared to more classical analysis as pH, C, N, P, texture…
- lack of harmonization (see below)

Major weaknesses/limitations in terms of soil monitoring harmonization
Within WP6 (see D6.3) during the stocktake exercise the question of harmonization was raised. With a few exceptions, the countries do not want to change their protocols (from the design, the sampling to the analytical part) to stock to a new harmonized one. A majority of the countries would accept to add new monitoring sites (e.g. that could be in common with LUCAS) and some may also, with a proper

budget, consider double sampling/analysis to compare their results with LUCAS ones. Such situation was found quite normal as there are quite old soil monitoring networks (e.g. started in the 80's), with several campaigns already completed and that any change may impair the use of existing data, unless comparison exercises can be made to develop transfer functions from past situation to the new one. However, this will require more resources and "*lots of soil monitoring networks struggle each year just to maintain the existing*".

VII: Recommendations for future soil monitoring

Within SIREN project a stocktake of indicators used and monitored in the countries was made where it appears that the largest commonality in indicators implemented by Member States is the quantification of soil organic carbon (stocks and changes). A clear omission for almost all countries relates to soil biological indicators, addressing soil biodiversity either with respect to structural aspects (species richness, etc.), or functional aspects (associated with soil functions and provision of services), or both. Indicators for water regulation and persistent organic contaminants are also scarcely implemented, whilst cost-effective methods have come available. **Such parameters and measurements should be pushed ahead.**

National evaluation criteria for soil quality indicators such as references and target values have been implemented scarcely; these primarily concern compost, sludge, soil and food contaminants or macronutrients in association to allowable fertilisation quota and ground- and surface water protection, rather than soil functions relating to service provision beyond food production and environmental standards. Particularly, no references or target values exist for soil organic carbon stocks and sequestering (except for 'no nett loss'). **Such benchmark values should now be developed to support the implementation of EU policies on soil.**

VIII: Existing approaches for monitoring of urban, industrial and natural areas, if considered.

Not considered in EJP SOIL as it deals with agricultural soil.

IX: Additional information

Website: https://ejpsoil.eu/

List of relevant deliverables from EJP SOIL :

- D2.2. Stocktaking on soil quality indicators and associated decision support tools, including ICT tools. https://ejpsoil.eu/fileadmin/projects/ejpsoil/WP2/Deliverable_2.2_Stocktaking_on_soil_quality_indicators_and_associated_decision_support_tools__including_ICT_tools.pdf
- D6.1. Harmonized procedures for creation of databases and maps https://ejpsoil.eu/fileadmin/projects/ejpsoil/WP6/EJP_SOIL_D6.1_Report_on_harmonized_procedures_for_creation_of_databases_and_maps__final.pdf
- D6.3. Proposal of methodological development for the LUCAS programme in accordance with national monitoring programmes. https://ejpsoil.eu/fileadmin/projects/ejpsoil/WP6/EJP_SOIL_Deliverable_6.3_Dec_2021_final.pdf
- SIREN web page: https://ejpsoil.eu/soil-research/siren (with report and policy brief)

SERENA - project brief

I: Project ID and objective

Project details	
Name and acronym:	SERENA - **S**oil **E**cosystem se**R**vices and soil threats mod**E**lling a**N**d m**A**pping
Funding programme:	EJP SOIL 2nd Internal Call – SE2/INDICATORS1 - Modelling soil functions and soil threats for mapping soil quality, soil functioning and ecosystem services.
Countries involved:	Czech Republic, Denmark, Estonia, France (coordinator), Hungary, Ireland, Italy (co-coordinator), Latvia, Lithuania, Netherlands, Poland, Portugal, Slovakia, Spain
Project duration *(start year and end year):*	2021-2024

Project main objective:
The ongoing shift from a merely productive conception of soils towards a more integrative vision of multifunctional soil quality requires a **shared analysis of concepts and definitions**, and the integration of innovative assessment tools into land planning and soil policies at different scales. SERENA intends to meet these requirements by putting relevant stakeholders at the core of the project, and by **providing co-developed indicators and related interpretation values**, able to report both on **soil degradation** and **soil-based ecosystem services**. Using relevant information on **soil quality** and **soil health**, SERENA will jointly evaluate **bundles** of soil-based ecosystem services and soil threats, and model their **evolution depending on climate and management**, from the **local** to the **European scales**.

II: Monitoring level considered:

There is **no collection of data in the SERENA project**, but we do use existing measurements stored in national or EU databases. However, the target scales for the evaluations and mapping of the projects are :

- **regional** level (especially for countries where the soil databases are available at the regional level and not at the national one)
- **national** level
- **EU** level

III: Indicators addressed in soil monitoring described in the project

Mission indicators:
The SERENA project does not measure any data, but uses data from existing databases, to evaluate the soil threats and the soil-based ecosystem services at both the national and EU scales.

The soil-based ecosystem services (SES) addressed in the SERENA project are: **Primary/biomass production, GHG and Climate regulation/Carbon sequestration, Erosion control, Hydrological control, Habitat for biodiversity, Pest and disease control, Environmental Pollution control.**

The soil threats (ST) addressed in the SERENA project are: **SOC loss, soil erosion, soil compaction, drought, nutrient imbalance, loss of soil biodiversity, soil sealing, soil acidification, soil contamination, water logging, salinization.**

The member states have prioritized threats and ecosystem services according to their willings, and are currently making the evaluation at the national scale for their 2-3 main selected SES and ST. The indicators they use depend on the data available in their country.

At the EU scale, we have prioritized the main SES and ES of interest at the EU scale which are:

- SES
  - Primary biomass production
  - GHG/Climate regulation
  - Erosion control
  - Hydrological control
- ST
  - SOC losses
  - Soil erosion
  - Soil compaction
  - Soil sealing

The indicators are not yet definitely stabilised. However, in the following list are those which are already selected or will be probably selected, especially at the EU scale. Others can somehow have been selected for the evaluations at the national scale in each country.

- presence of soil pollutants, excess nutrients and salts*;*
  - ***trace elements,***
- **soil organic carbon stock or content**;
- **soil bulk density**
- soil **nutrients** and acidity (pH) *(essential nutrients: N, P, K, S, Ca; micronutrients)*;

How soil health/quality indicators are estimated

The SERENA project does not address soil quality or soil health directly, but evaluate indicators of soil-based ecosystem services and soil threats. These indicators are either already available in databases, or evaluated by pedotransfer functions if needed. In the last period of the project, some of them will also be evaluated by modelling under scenarios of change. The scenarios are currently being selected, as well as the models to be used.

Other indicators *(not listed above, e.g. land take indicator, soil artificial surface)* **describing soil health included in monitoring programmes** *(please specify)*:
not relevant for SERENA

Short summary of monitoring described in the project
not relevant for SERENA

Is any soil health index proposed/developed?
At the moment, we do not have any specific soil health index in SERENA, but one could be developed if it appears that it makes sense for the MS to have a common one.

IV: Was soil monitoring accompanied by any surveys on soil management?

For the evaluation at the EU scale, we do not use any soil management information.

For the evaluation at the national scales, it could be possible that some states are actually using such data (more information will be available for this question when this action of the project will be finished).

V: Are any limit values (critical limits) (e.g. threshold values, reference values, relative change) used/proposed for soil health monitoring?

The limit values are not directly addressed in SERENA. However, the results could be compared to either national values, of the values proposed by the EU Soil law.

VI: Gaps and limitations in soil monitoring defined by the project

Gaps in soil monitoring
not relevant for SERENA (no monitoring)

Major weaknesses/limitations in terms of soil monitoring harmonization
not relevant for SERENA (no monitoring)

VII: Recommendations for future soil monitoring

This question could be discussed at the end of the project, when we will have compared all the national SES and ST evaluations and discussed if we can harmonise them.

VIII: Existing approaches for monitoring of urban, industrial and natural areas, if considered.

not relevant for SERENA (which addressed only agricultural soils, in the framework of EJP SOIL)

IX: Additional information

Website: https://ejpsoil.eu/soil-research/serena

MINOTAUR (EJP SOIL) - project brief

I: Project ID and objective

Project details	
Name and acronym:	Modelling and mapping soil biodiversity patterns and functions MINOTAUR (EJP Soil)
Funding programme:	Horizon 2020 - EJP Soil internal
Countries involved:	Italy, France, Netherlands, Austria, Czech Republic, Ireland, Slovenia, Sweden, Switzerland
Project duration *(start year and end year):*	2021-2024

Project main objective:
MINOTAUR aims to provide models, maps and policy-relevant indicators with validated reference values for monitoring soil biodiversity and associated functions. Moreover, it will aim to understand how agricultural practices can contribute to climate change mitigation and adaptation at regional and national levels across the EU. The main aim is to identify and select relevant taxonomical and functional indicators for soil biodiversity and associated soil functions, document their status and trends in time and space across Europe, as well as to assess vulnerability of biodiversity indicators to climate change and sensitivity for management practices.

II: Monitoring level considered:

- **regional inside a country**
- **national**
- **European regional or transborder *(more than one country covered by soil monitoring)***
- **European (*continental*)**

III: Indicators addressed in soil monitoring described in the project

Mission indicators:
- **soil organic carbon stock or content;**
- **soil biodiversity; *please specify soil biodiversity indicator***s:*
  - ***functional indicators (e.g., enzymatic activity, microbial biomass, microbial respiration)***
  - ***structural indicators:*** *microbial diversity (**bacteria, fungi**, archaea, viruses, algae); micro-meso-macrofauna (e.g., earthworms, **ants**, termites, millipedes, dung beetles, springtails)*

IV: Was soil monitoring accompanied by any surveys on soil management?

V: Are any limit values (critical limits) (e.g. threshold values, reference values, relative change) used/proposed for soil health monitoring?

Threshold values for biological indicators will be assessed.

VI: Gaps and limitations in soil monitoring defined by the project

Gaps in soil monitoring

Major weaknesses/limitations in terms of soil monitoring harmonization

According to the proposed Soil Monitoring Directive, the assessment of soil biodiversity should only be based on baseline soil respiration. This approach to biodiversity assessment was assessed by the project team as insufficient, and the document "*Feedback to the Soil Monitoring Law from the EJP SOIL internal project 'MINOTAUR' on soil biological indicators*" on soil biological indicators' gives further preliminary recommendations.

Source:https://ejpsoil.eu/fileadmin/projects/ejpsoil/WP8/Soil_monitoring/2023-11-03_EJP_SOIL_Feedback_to_Soil_Monitoring_Law___MINOTAUR___Biological_Indicators.pdf

VII: Recommendations for future soil monitoring

Preliminary recommendations from the above mentioned document and MINOTAUR project for the future soil monitoring:

- a two "tiered system" approach; a first set of harmonized indicators is recommended in all cases, covering both functional and structural biodiversity, and for which standard methods are available (Tier I group).
- If Tier I results indicate a "not healthy" status, MS may also locally apply other indicators (tier II group), to better identify the problem (soil threats) and/or to inform decision pertaining to land management.

Aspect of soil degradation	Current directive Soil descriptor (Annex I)	**Recommendation**
Loss of soil biodiversity	Soil basal respiration (mm^3 O_2 g^{-1} hr^{-1}) in dry soil Member States may also select other optional soil descriptors for biodiversity such as: - metabarcoding of bacteria, fungi, protists and animals; - abundance and diversity of nematodes; - microbial biomass; - abundance and diversity of earthworms (in croplands); - invasive alien species and plant pests	Tier I group: Functional diversity: - soil basal respiration - microbial biomass; - enzyme activity (fluorogenic substrates); Structural diversity: - metabarcoding of microorganisms (bacteria, fungi); - abundance, diversity and ecological indices of nematodes; - abundance, diversity and ecological indices of microarthropods; - abundance, diversity and ecological indices of earthworms;

		Member States may also select other optional soil descriptors for biodiversity (Tier II group), such as: - Specific groups and functional genes (qPCR) - soil metagenomics for biomarkers of soil health - microbial necromass - Soil fauna activity (i.e. organic matter degradation) - N mineralization - Ecophysiological profile (AWCD) - invasive alien species and plant pests

Source:https://ejpsoil.eu/fileadmin/projects/ejpsoil/WP8/Soil_monitoring/2023-11-03_EJP_SOIL_Feedback_to_Soil_Monitoring_Law___MINOTAUR___Biological_Indicators.pdf

VIII: Existing approaches for monitoring of urban, industrial and natural areas, if considered.

The MINOTAUR project is focused on agricultural soils.

IX: Additional information

WEBSITE: https://ejpsoil.eu/soil-research/minotaur

STEROPES - project brief

I: Project ID and objective

Project details	
Name and acronym:	Stimulating novel Technologies from Earth Remote Observation to Predict European Soil carbon (STEROPES)
Funding programme:	EJP Soil
Countries involved:	France, Sweden, Italy, Switzerland, Spain, Portugal, Czech Republic, The Netherlands, Latvia, Lithuania, Denmark, Turkey, Belgium, Poland
Project duration *(start year and end year):*	2021-2024

Project main objective:

To overcome the limitations of static soil maps by putting the use of satellite time series forward (especially Sentinel 2), to test their potential to predict cropland soil organic carbon content over various pedoclimatic conditions and cropping systems across Europe soil; And studying of the influence of disturbing or influencing – sometimes facilitating – factors for SOC prediction (soil moisture (Sentinel 1 is taken into account for soil moisture), crop residues on the soil surface, presence of vegetation, salinity …)

Carbon in deep soil layers is highly dependent on agricultural practices (review article by Emmanuelle Vaudour in 2022); this project is for conventional agriculture with soil tillage; it should be adapted for conservation agriculture (i.e. no/little tillage) or for the agro-ecological transition, because of their impact on the vertical distribution of organic carbon.

The project is more concerned with prediction than monitoring (in fact, monitoring for storage practices: in particular, spreading OM and practices in general).

II: Monitoring level considered:

- field scale (or collection of test results requested by farmers or cooperatives and provided by soil testing laboratories)
- farm scale
- **regional inside a country, *including subregional: small historical regions*** and small agricultural areas (not necessarily the official regions of the Member States)

III: Indicators addressed in soil monitoring described in the project

Mission indicators:

- presence of salts
- **soil organic carbon content** *mainly on bare soils. However, STEROPES will try to work on other contexts (conservation agriculture (i.e. without soil tillage), grasslands …).*

Another project is starting with Spain on vineyard and olive trees (with INRAE-France);

- soil structure and absence of soil sealing and erosion;
- soil acidity (pH)
- vegetation cover (*diversity of vegetation cover*)*, because it is a disruptive factor*;
- landscape heterogeneity *including geomorphology*.

How soil health/quality indicators are estimated
C (parallel or successive extractions, total combustion, spectroscopic methods)

Comments on spectroscopic methods: Limits and uncertainties linked with the depth of soil, the impact of vegetation covering the soil (grassland, forest, annual crops etc.), the impact of other soil characteristics (moisture, surface roughness …)

Other indicators *(not listed above, e.g. land take indicator, soil artificial surface)* **describing soil health included in monitoring programmes** *(please specify)*:

- clay content (lab);
- soil moisture (Theia (Sentinel 1 + Sentinel 2 to take account of vegetation heights), field monitoring);
- We're more concerned with prediction than monitoring (in fact, monitoring for storage practices: in particular, spreading OM and practices in general).

Short summary of monitoring described in the project

- *the sampling procedure:* Problem with no clear answer for them (as numerous data were obtained previously by other programs). One of their objectives is to identify how satellite images can help to reduce soil samplings. They use both data already acquired and new data.
- *depth of soil considered:* As they work on soils managed under conventional agriculture (with ploughing), they may consider the ploughing depth (0-25 cm or 0-30 cm), the surface soil horizon, or sometimes take 5 or 8 cm samples.
- *experimental procedure:* number of samples per site or location, approximate mass of each sample and approximate distance between sampling points, homogenisation procedure (or not) in the laboratory,
- *frequency of sampling:* In France, they use mainly data collected by the French soil quality network (Réseau de Mesure de la Qualité des Sols (RMQS)). Each site is sampled every 15-16 years.

Is any soil health index proposed/developed?

IV: Was soil monitoring accompanied by any surveys on soil management?

yes when it was possible (extremely difficult to obtain the information, especially on stocking management)

V: Are any limit values (critical limits) (e.g. threshold values, reference values, relative change) used/proposed for soil health monitoring?

This is actually under study

VI: Gaps and limitations in soil monitoring defined by the project

Gaps in soil monitoring
Not monitored: indirect impacts on erosion, compaction, biodiversity, fertility, immobilisation of pollutants

Major weaknesses/limitations in terms of soil monitoring harmonization
- Remote sensing data may be disturbed by surface factors.
- There is the problem of spatial resolution (In France, scientists are waiting for the CNES Biodiversity mission to have fine spatial resolution.
- Remote sensing (Sentinel 2) only provides information on the upper soil layer. (Scientists in the STEROPES project need non-spectral variables to extrapolate soil organic carbon at depth. Geophysical data provide information about the deeper layers of the soil (Sentinel 1 also provides information at greater depths)).
- STEROPES project focuses on field crops. Others contexts have to be studied: agroforestry, vines with inter-rows of bare soil or grass, orchards, and other cultivated soils.

VII: Recommendations for future soil monitoring

Conventional measurements (field measurements and lab measurements after soil sampling) are essential: remote sensing allows interpolations in space and time between direct measurements that are rare and too far apart in space.
Remote sensing can be useful for updating maps and defining spatial uncertainties.

VIII: Existing approaches for monitoring of urban, industrial and natural areas, if considered.

The STEROPES project is also looking at peri-urban agriculture, with specific issues of soil pollution.

IX: Additional information

Website: https://ejpsoil.eu/soil-research/steropes

HoliSoils- project brief

I: Project ID and objective

Project details	
Name and acronym:	Holistic management practices, modelling and monitoring for European forest soils (HoliSoils)
Funding programme:	H2020
Countries involved:	Finland, Czech Rep., France, Germany, Spain, The Netherlands, Sweden, Romania, UK, Lithuania, Slovakia, Urugway, Japan,
Project duration *(start year and end year):*	2021 - 2025

Project main objective:
The project will develop a harmonised soil monitoring framework to ensure meeting climate and sustainability goals. Through a collaborative, multi-actor approach, the project identifies and tests soil management practices. The goal is to develop effective numerical forecasting of soil-based greenhouse gas mitigation practices and ensure sustainable provision of various ecosystem services. To develop tools for soil monitoring, HoliSoils incorporates novel methodologies and expert knowledge on analytical techniques, data sharing, soil properties and biodiversity, and processes with model development.

II: Monitoring level considered *(please indicate appropriate from the list below)*

- **regional inside a country**
- **national**
- **European regional or transborder *(more than one country covered by soil monitoring)***
- **European (*continental*)**

III: Indicators addressed in soil monitoring described in the project

Mission indicators

- soil organic carbon stock or content;
- soil biodiversity;
- soil nutrients and acidity (pH);
- vegetation cover;
- landscape heterogeneity;
- forest cover

Short summary of monitoring described in the project *(issues relevant for the monitoring harmonisation*)
For forest areas the HoliSoils develops a database of soil spatial data and soil properties and map layers as data source for web services and API development which in turn enable data integration into third party systems requiring HoliSoils data.

VI: Gaps and limitations in soil monitoring defined by the project

The sampling design – and therefore, the exact GHG monitoring method - (grid size, plot size, sampling depths, number of soil samples etc.) often remains unclear, especially if the inventory was not part of a project like BioSoil or ICP Forest. One problem here is, amongst others, an outdated online documentation with invalid access or publications with restricted access.

VII: Recommendations for future soil monitoring

Recommendations regarding SOC models dedicated to forest soils: "Current limitation is a lack of independent validation based on SOC network measurements. Filling this gap will be crucial to evaluate objectively regional to global SOC predictions in the context of climate and land use changes. Reuse of highly valuable data sets and novel measurement networks will be central to this effort. In particular, existing decadal field experiments represent a valuable source of data. They provide long-term time-series data on SOC stocks in different climatic conditions, but remain underutilised. At a larger scale, validations against observations from measurement networks allow the predictive value of SOC models to be assessed under a vast range of land-use and pedoclimatic contexts.
National and macro-regional soil monitoring networks are routinely resampled and data are becoming more available (e.g., with the second campaign of the French Soil Network Measurement and fourth resampled of the European LUCAS topsoil network and with the regional or national soil monitoring systems existing in 18 European countries), and will therefore enable validating models in a large set of contexts and at large spatial and temporal scales. Some existing limitations still need to be overcome. In particular, the different soil databases already in use require harmonisation in terms of spatial resolution, reported variables and measurement methods. Because data scarcity is still largely limiting large-scale validation, global datasets, such as the Soil Respiration Database, remain invaluable to validate the ability of models to predict the spatial variability of C fluxes from soils." Source: Le Noë, J., Manzoni, S., Abramoff, R. et al. Soil organic carbon models need independent time-series validation for reliable prediction. Commun Earth Environ 4, 158 (2023). https://doi.org/10.1038/s43247-023-00830-5

VIII: Existing approaches for monitoring of urban, industrial and natural areas, if considered.

The project is ongoing. The report on current status of monitoring GHG in forest areas has been released. It reveals that there are three main methodological categories for GHG monitoring for forest land: no monitoring and assuming no stock change in mineral forest soil due to no changes in land use, management and/or species; national inventory/inventories or monitoring systems in forest soils (representative or not representative for whole country); calculations of C stocks and stock changes by models.

IX: Additional information

https://holisoils.eu/

LUCAS Soil - project brief

I: Project ID and objective

Project details	
Name and acronym:	LUCAS Soil
Funding programme:	JRC/EUROSTAT
Countries involved:	All EU countries
Project duration *(start year and end year):*	started in 2009 with several campaigns (2012, 2015, 2018 and 2022)

Project main objective:
The 'Land Use/Cover Area frame statistical Survey Soil' (LUCAS Soil) is an extensive and regular topsoil survey that is carried out across the European Union to derive policy-relevant statistics on the effect of land management on soil characteristics. Approximately 45 000 soil samples have been collected from several time-periods, 2009–2012, 2015, 2019 and 2022. The sampling design is based on the LUCAS campaign[1].

II: Monitoring level considered:

- **European regional or transborder**
- **European**

EU scale is investigated but depending on the number of points in each country, **national** assessments may also be developed.

III: Indicators addressed in soil monitoring described in the project

Mission indicators

- **presence of soil pollutants, excess nutrients and salts***:*
  - *trace elements,*
  - *organic pollutants (e.g., pesticides, 2 antibiotics) in pilot study (2018)*
- **soil organic carbon stock or content;**
- **soil structure including soil bulk density and absence of soil sealing and erosion;**
- **soil biodiversity** *indicators:*
  - *functional indicators (e.g., enzymatic activity, microbial biomass, microbial respiration)*

[1] Following a decision of the European Parliament, the European Statistical Office (EUROSTAT) in close cooperation with the Directorate General responsible for Agriculture and the technical support of the JRC, is organising regular, harmonised surveys across all Member States to gather information on land cover and land use. This survey is known as LUCAS (Land Use/Cover Area frame statistical Survey). The name reflects the methodology used to collect the information. Estimates of the area occupied by different land use or land cover types are computed on the basis of observations taken at more than 250,000 sample points throughout the EU rather than mapping the entire area under investigation. By repeating the survey every few years, changes to land use can be identified.

- *<u>structural indicators</u>: microbial diversity (bacteria, fungi, archaea, viruses, algae); micro-meso-macrofauna (e.g., earthworms, ants, termites, millipedes, dung beetles, springtails)*

- **soil nutrients and acidity (pH)** *(essential nutrients: N, P, K, S, Ca; micronutrients)*;
- **vegetation cover**[2] (*diversity of vegetation cover*);
- **landscape heterogeneity**[2] *(farmland, forestry, urban green infrastructure, diversity of landscape elements)*;
- **forest cover**[2] *(area of forests, area of wooded lands, share of non-native tree species)*

All soil mission indicators are investigated in LUCAS Soil.

How soil health/quality indicators are estimated

Table and text from: *Orgiazzi, A., Ballabio, C., Panagos, P., Jones, A., & Fernández-Ugalde, O. (2018). LUCAS Soil, the largest expandable soil dataset for Europe: a review. European Journal of Soil Science, 69(1), 140-153.*

Table 1 Structure of LUCAS Soil survey over the sampling years

MODULE	Type of analysis	Year of survey				
		2009–2012	2015	2018	2021	→
MODULE 1 Physico-chemical properties	Coarse fragments (>2 mm)/%					
	PSD[1]: clay, silt, sand/%					
	pH ($CaCl_2$, H_2O)					
	Organic carbon/g kg^{-1}					
	Carbonate content/g kg^{-1}					
	Total nitrogen content/g kg^{-1}					
	Extractable potassium content/mg kg^{-1}					
	Phosphorous content/mg kg^{-1}					
	Cation exchange capacity/cmol(+) kg^{-1}					
	Electrical conductivity/mS m^{-1}					
	Metals					
	Multispectral properties					
	Mineralogy					
MODULE 2 Soil biodiversity	Bacteria and Archaea (16S rDNA)					
	Fungi (ITS)					
	Eukaryotes (18S rDNA)					
	Microfauna (nematodes)					
	Mesofauna (arthropods)					
	Macrofauna (earthworms)					
	Metagenomics					
MODULE 3 Bulk density	Bulk density					
	Soil moisture					
MODULE 4 Field measurements	Soil erosion by water and wind					
	Thickness of organic layer in Histosols					
	Soil structure					
MODULE 5 Pollution	Organic pollutants					
	Pesticides residues					
Possibility to include new modules						

PSD[1], particle-size distribution.
Different modules form the overall structure of the survey; each module corresponds to different types of analyses. The analyses are repeated at a standard time interval, namely every 3 years. Types of analyses already established (full colour cells) for the campaign scheduled for 2018. Possible analyses for 2021 (dotted cells) are still under discussion and there will be the opportunity to implement the survey further by including new modules.

[2] Using the LUCAS dataset those indicators not based on soil samples can be calculated on the same locations.

The detailed methods are listed below:

Coarse fragments: in all samples, macroscopic roots and all particles, mineral and organic, with a diameter larger than 2 mm, are removed by dry sieving. The mineral particles not passing the 2-mm sieve are weighed separately to determine the content of coarse fragments.

Particle-size distribution: percentages of clay, silt and sand in mineral soil material are measured by laser diffraction following the ISO (International Organization for Standardization) procedure number 13320:2009 (ISO, 2009). A laser diffraction analyser able to measure particle sizes in the 0.02 µm to 2 mm range is used. The particle-size distribution (PSD) is measured on two or three subsamples. The third sample is measured only when the two previous samples are significantly different.

Soil pH: is measured following the ISO 10390:1994 standard (ISO, 1994a). The method includes the determination of pH in both water and $CaCl_2$.

Cation exchange capacity: is measured following the ISO 11260:1994 protocol (ISO, 1994b). This procedure determines the concentrations of exchangeable Na, K, Ca and Mg in soil.

Organic carbon content: is measured following the ISO 10694:1995 protocol (ISO, 1995b). Briefly, the total carbon content of the soil sample is determined after dry combustion with an elemental analyser. The organic carbon content is calculated from this content after correcting for carbonate content in the sample. In the absence of carbonates, total carbon content is equal to organic carbon content of the sample.

Carbonate content: is quantified by the ISO 10693:1994 procedure (ISO, 1995a). This standard reproduces the Scheibler method (ASI, 1999).

Phosphorus (P) content: is measured by the ISO 11263:1994 protocol (ISO, 1994c). The method calculates the phosphorus soluble in a sodium hydrogen carbonate solution.

Total nitrogen (N) content: is measured in accordance with the ISO 11261:1995 protocol (ISO, 1995c). This method assesses the concentrations of ammonium-N, nitrate-N, nitrite-N and organic N present.

Extractable potassium (K) content: is determined following the Soil Survey Laboratory Manual produced by the United States Department of Agriculture Natural Resources Conservation Service (USDA NRCS, 2004).

Electrical conductivity: in an aqueous extract of soil is measured as described in the standard ISO 11265:1994 (ISO, 1994d). The measurement indicates the content of water-soluble electrolytes (salts) in a soil.

Metals: A selection of metals is measured by inductively coupled plasma–optical emission spectrometry. These include arsenic (As), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), iron (Fe), magnesium (Mg), manganese (Mn), nickel (Ni), lead (Pb), antimony (Sb), vanadium (V) and zinc (Zn). Detailed explanation of the methodology is reported in Tóth et al. (2016).

Multispectral analysis: Diffuse reflectance was determined with a spectroscope that records the full continuous reflectance spectrum from 400 to 2500 nm with a spectral resolution of 2 nm. Details on the methodology are described by Nocita et al. (2014).

X-ray diffraction: Mineralogical composition of the clay fraction (<2 µm) is analysed by X-ray diffractometry (XRD). The XRD patterns are obtained under the following conditions: air-drying, ethylene glycolation, heating at 110 °C, 350 °C and 550 °C, saturation with Mg and K ions, and solvation with glycerol. Interpretation and quantification of XRD patterns is carried out with the NEWMOD software.

Other than these physicochemical properties, additional variables can be assessed. For example, soil classification based on visual assessment (Munsell soil colour charts) may be carried out from photographs of a soil sample.

In 2018, other analyses were performed on *pesticides* and on *biodiversity indicators*. Detailed methods can be found in the following publications:

- Silva, V., Mol, H. G., Zomer, P., Tienstra, M., Ritsema, C. J., & Geissen, V. (2019). Pesticide residues in European agricultural soils–A hidden reality unfolded. Science of the Total Environment, 653, 1532-1545.
- European Commission, Joint Research Centre, Vieira, D., Franco, A., De Medici, D., et al., Pesticides residues in European agricultural soils : results from LUCAS 2018 soil module, Publications Office of the European Union, 2023, https://data.europa.eu/doi/10.2760/86566
- Orgiazzi, A., Panagos, P., Fernández-Ugalde, O., Wojda, P., Labouyrie, M., Ballabio, C., ... & Jones, A. (2022). LUCAS Soil Biodiversity and LUCAS Soil Pesticides, new tools for research and policy development. European Journal of Soil Science, 73(5), e13299.
- Smith, L. C., Orgiazzi, A., Eisenhauer, N., Cesarz, S., Lochner, A., Jones, A., ... & Guerra, C. A. (2021). Large-scale drivers of relationships between soil microbial properties and organic carbon across Europe. Global Ecology and Biogeography, 30(10), 2070-2083.
- Labouyrie, M., Ballabio, C., Romero, F., Panagos, P., Jones, A., Schmid, M. W., ... & Orgiazzi, A. (2023). Patterns in soil microbial diversity across Europe. Nature Communications, 14(1), 3311.
- Köninger, J., Ballabio, C., Panagos, P., Jones, A., Schmid, M. W., Orgiazzi, A., & Briones, M. J. (2023). Ecosystem type drives soil eukaryotic diversity and composition in Europe. Global Change Biology.

Other indicators *(not listed above, e.g. land take indicator, soil artificial surface)* **describing soil health included in monitoring programmes** *(please specify)*:

Short summary of monitoring described in the project

The sampling strategy and procedure changed with time. The last version can be found in:

Jones, A., Fernandez Ugalde, O., Scarpa, S. and Eiselt, B., LUCAS Soil 2022, EUR 30331 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-21079-5, doi:10.2760/74624, JRC121253. DOI: 10.2760/74624 (online)

Is any soil health index proposed/developed?

Not yet

IV: Was soil monitoring accompanied by any surveys on soil management?

Mainly land use / land cover is noted.

V: Are any limit values (critical limits) (e.g. threshold values, reference values, relative change) used/proposed for soil health monitoring?

Not included in the LUCAS manual.

VI: Gaps and limitations in soil monitoring defined by the project

Gaps in soil monitoring

Lots of parameters are measured on the samples based on several modules that have been added with time. It finally includes main of the indicators available and pushed by science, not on always on all samples but on part of them.

Major weaknesses/limitations in terms of soil monitoring harmonization

The LUCAS Soil protocol is homogeneous across EU but in between campaigns changes may have occur in analytical methods (e.g. for texture determination). This needs to be checked when using the data from different campaigns.

VII: Recommendations for future soil monitoring

Identify ways to collaborate with national monitoring networks as having common sampling sites.

VIII: Existing approaches for monitoring of urban, industrial and natural areas, if considered.

Some urban sites are included in the latest campaigns.

IX: Additional information

Website: https://esdac.jrc.ec.europa.eu/projects/lucas

ORCaSa - project brief

I: Project ID and objective

Project details	
Name and acronym:	Operationalising the International Research Cooperation on Soil Carbon (ORCaSa)
Funding programme:	Horizon Europe
Countries involved:	EU countries (France, Netherlands, Belgium, Spain), Ghana, Australia, Brazil, Vietnam, USA
Project duration *(start year and end year):*	2022-2025

Project main objective:
The project seeks to address the issue of increasing carbon emissions from human activities, which have led to a disruption in the balance of organic carbon absorbed and stored in the soil to support plant growth.

II: Monitoring level considered:

- field scale (or collection of test results requested by farmers or cooperatives and provided by soil testing laboratories)
- farm scale
- regional inside a country
- national

III: Indicators addressed in soil monitoring described in the project

Mission indicators:

- **soil organic carbon stock or content**;
- soil structure including soil bulk density and absence of soil sealing and erosion (maybe: not sure);
- vegetation cover (*diversity of vegetation cover*); (for soil organic C objectives)
- landscape heterogeneity *(farmland, forestry, urban green infrastructure, diversity of landscape elements)*; (for soil organic C objectives)
- forest cover *(area of forests, area of wooded lands, share of non-native tree species)* (for soil organic C objectives)

How soil health/quality indicators are estimated
Review of existing elements and measurements : ORCaSa is a CSA, not RIA
ORCaSa will identify:
- models (combining crop model, climate model, soil functioning),
- measurements (satellite-based Earth Observation, flux tower for H_2O, CO_2 …),
- agricultural data (crop exportations, inputs),

- and methods that can help in estimating soil organic carbon, e.g. by defining in situ soil sampling strategies.

Satellite-based Earth Observation data are used in a variety of ways. Some of these data can be used for assimilation into models, i.e. to correct them over time.

Other indicators *(not listed above, e.g. land take indicator, soil artificial surface)* **describing soil health included in monitoring programmes** *(please specify)*:

Soil organic C indicator only (to favour climate change mitigation)

Short summary of monitoring described in the project
CSA: no sampling (satellite data) to help to identify/optimise soil sampling sites.

Is any soil health index proposed/developed?

IV: Was soil monitoring accompanied by any surveys on soil management?

Agricultural data (crop exportations, inputs), and methods of soil management(and vegetation covers etc.)

V: Are any limit values (critical limits) (e.g. threshold values, reference values, relative change) used/proposed for soil health monitoring?

No

VI: Gaps and limitations in soil monitoring defined by the project

Gaps in soil monitoring

Major weaknesses/limitations in terms of soil monitoring harmonization

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VII: Recommendations for future soil monitoring

ORCaSa will propose a framework for soil organic C monitoring, reporting and verification (MRV) with impact on financial schemes: NDC (National determining contribution), Common Agriculture Politics (CAP) with ecoscheme, voluntary carbon market, In-setting, sampling …

VIII: Existing approaches for monitoring of urban, industrial and natural areas, if considered.

One of the program objectives: to define a framework for forest soils and urban soils

IX: Additional information

Website: https://irc-orcasa.eu/
Objective is not restricted to UE: IRC (International Research Consortium)

BENCHMARKS - project brief

I: Project ID and objective

Project details	
Name and acronym:	Building a European Network for the Characterisation and Harmonisation of Monitoring Approaches for Research and Knowledge on Soils BENCHMARKS
Funding programme:	Soil Mission HE
Countries involved:	Germany, Portugal, Spain, France, Italy, United Kingdom, Netherlands, Slovenia, Austria, Czechia, Norway, Finland
Project duration *(start year and end year):*	2023-2027

Project main objective:

BENCHMARKS project will co-design an Integrated Soil Health Monitoring Framework, which will build upon the assessment of soil-based ecosystem functions to co-develop an interactive soil health dashboard. The aim is to guide the selection of appropriate soil health indicators, soil health assessment and indexation, and recommendation of management practices to support soil health. The dashboard will be designed for different stakeholders in **urban, agricultural and forestry land use** systems. Its proposed indicators (sample-based measurements and data, and model-derived statistics), space and citizen science observations will be tested in landscape case studies across Europe.

II: Monitoring level considered *(please indicate appropriate from the list below)*

- **European regional or transborder *(more than one country covered by soil monitoring)***
- **European (*continental*)**

III: Indicators addressed in soil monitoring described in the project

Mission indicators:

- **soil organic carbon stock or content;**
- **soil structure including soil bulk density and absence of soil sealing and erosion;**
- **soil biodiversity***:*
  - ***structural indicators***); ***micro-meso-macrofauna*** *(e.g.,* ***earthworms)***
- **soil nutrients and acidity (pH) *(essential nutrients: N, P, K, S, Ca; micronutrients)*;**
- **landscape heterogeneity *(farmland, forestry, urban green infrastructure, diversity of landscape elements)*;**

IX: Additional information

WEBSITE: https://soilhealthbenchmarks.eu/

AI4SOILHEALTH – project brief

I: Project ID and objective:

Project details	
Name and acronym:	Accelerating collection and use of soil healt information using AI technology to support the Soil Deal for Europe and EUSO (AI4SOILHEALTH)
Funding programme:	Soil Mission HE
Countries involved:	Finland, Sweden, Denmark, United Kingdom, Spain, France, Italy, Croatia, Greece
Project duration *(start year and end year):*	2023-2026

Project main objective:
The AI4SoilHealth project aims to establish a Europe-wide digital infrastructure using advanced AI methods and soil health understanding. This infrastructure will create a Soil Digital Twin for monitoring soil health metrics, in line with the European Commission's goal of promoting healthy soils by 2030. The project consists of seven work-packages including stakeholder engagement, methodology development, in-situ monitoring tools, harmonized soil monitoring services, multi-actor engagement pilots, and literacy/communication activities. Key deliverables will include a Soil Health Index methodology, Rapid Soil Health Assessment Toolbox, AI4SoilHealth Data Cube for Europe, Soil-Health-Soil-Degradation-Monitor, and AI4SoilHealth API and Mobile phone App. The project will involve target users' feedback to improve the tools, and the datasets will be made available under an Open Data license. The project also aims to provide a Soil Health Index certification system to support landowners and policy makers in line with the new Green Deal for Europe.

II: Monitoring level considered:

- **European regional or transborder**
- **European (*continental*)**

III: Indicators addressed in soil monitoring described in the project

Mission indicators:

- **soil organic carbon stock or content;**
- **soil structure including soil bulk density and absence of soil sealing and erosion;**
- **soil nutrients and acidity (pH) *(essential nutrients: N, P, K, S, Ca; micronutrients)*;**

IX: Additional information:

WEBSITE: https://ai4soilhealth.eu/

Carbon Farming CE – project brief

I: Project ID and objective:

Project details	
Name and acronym:	Circular BioEconomy Market Uptake and Policy Support in Central Europe (Carbon Farming CE)
Funding programme:	Interreg Central Europe
Countries involved:	Slovenia, Hungary, Italy, Poland, Austria, Slovakia, Croatia, Germany, Czech Rep.
Project duration *(start year and end year):*	2023-2026

Project main objective:

Carbon farming is the process of changing agricultural practices to increase the amount of carbon stored in the soil, or to reduce greenhouse gas emissions from livestock. As it is still underused in central Europe, the Carbon Farming – CE project wants to make regions more familiar with the concept. The partnership adapts and tests various techniques and business models and develops a monitoring tool for transnational, standardised carbon sequestration.

II: Monitoring level considered:

- **European regional or transborder**
- **European (*continental*)**

III: Indicators addressed in soil monitoring described in the project

Mission indicators:

- **soil organic carbon stock or content;**
- **soil nutrients and acidity (pH) *(essential nutrients: N, P, K, S, Ca; micronutrients)*;**

IX: Additional information:

WEBSITE: https://www.interreg-central.eu/projects/carbon-farming-ce/

Appendix 3 Results of stocktaking of national soil monitoring

Soil monitoring programs:

- Soil monitoring in France: case study 1.1, 1.2, 1.3
- Soil monitoring in Spain: case study 2.1, 2.2, 2.3, 2.4, 2.5, 2.6
- Soil monitoring in Denmark: case study 3
- Soil monitoring in Poland: case study 4
- Soil monitoring in Norway: case study 5.1, 5.2, 5.2

Soil monitoring – France – case study 1.1

Sub-category	**Information collected**
	General information
Project/initiative name	**RMQS** **(French 'Réseau de mesure de la Qualité des Sols')**
	Description of monitoring
Land use type	All types (natural, forest, urban, post-industrial)
Scale	National scale
Level of implementation	Implemented
Frequency of monitoring	12-15 years
Type of threat monitored	soil organic carbon loss, nutrient imbalance, soil acidification, soil contamination, loss of soil biodiversity
Sampling strategy	4 composite samples (for 0-25 cm, 25-50 cm, 50-75 and 75-100 cm) made each of 25 sub-samples; Sampling area: 400 m^2 Sampling with auger. Every 12-15 years. Sampling for bulk density is made in a soil pit at three depths.
Sampling density	One site each 16 km x 16 km
	Indicators
Mission indicators	Soil organic carbon stock (depth) Soil structure including soil bulk density Soil biodiversity Soil nutrients and acidity (pH) Vegetation cover Landscape global description Forest cover
Additional indicators	AWC (Available Water Capacity) --> standard ? Biological activities (exo-enzyms) --> standard (cf. ref. internet)
Methods applied	Since now, no translation in soil health (e.g. by comparing actual values with threshold)
Limit values	For heavy metals, sometimes a comparison with threshold values proposed in the sewage sludge regulation.
	Additional information
Survey on soil management	Rotation, soil tillage, fertilization (mineral and/or organic), phyto-treatments, irrigation
Gaps/weaknesses identified in soil monitoring	Emerging contaminants and biodiversity (just beginning such characterizations)

Recommendations for future/ needs on harmonization	Better collaboration with LUCAS Soil
Data availability	Part is freely and available, another part with permission (free for research purpose with an agreement; otherwise, soil managements and actual GPS coordinates are not communicated).
Website	https://www.gissol.fr/le-gis/programmes/rmqs-34 https://www.iso.org/standard/67074.html https://hal.inrae.fr/hal-03823026

Soil monitoring – France – case study 1.2

Sub-category	Information collected
General information	
Project/initiative name	**BDAT**
Description of monitoring	
Land use type	Agricultural
Scale	National scale
Level of implementation	Implemented
Frequency of monitoring	Each year, but we collect Data from commercial Labs only every 5 years
Type of threat monitored	soil organic carbon loss, nutrient imbalance, soil acidification
Sampling strategy	Sampling strategy varying with samplers
Sampling density	---
Indicators	
Mission indicators	Soil organic carbon stock (depth) Soil nutrients and acidity (pH)
Additional indicators	---
Methods applied	(No for indicators, Standardized analysis methods for Lab procedures)
Limit values	No
Additional information	
Survey on soil management	No
Gaps/weaknesses identified in soil monitoring	Diversity of labs (and methods) and sampling strategies and sampling protocols
Recommendations for future/ needs on harmonization	The definition of common data standards to favour data exchanges (between private Labs and INRAE (GIS Sol))
Data availability	Only with permission of the Labs
Website	https://www.gissol.fr/le-gis/programmes/base-de-donnees-danalyses-des-terres-bdat-62

Soil monitoring – France – case study 1.3

Sub-category	Information collected
General information	
Project/initiative name	BTETM
Description of monitoring	
Land use type	Agricultural
Scale	National scale
Level of implementation	Implemented
Frequency of monitoring	Each year, but we collect Data every 10 years
Type of threat monitored	Soil contamination
Sampling strategy	Sampling strategy varying with samplers
Sampling density	---
Indicators	
Mission indicators	presence of soil pollutants excess nutrients and salts
Additional indicators	---
Methods applied	(No for indicators, Standardized analysis methods for Lab procedures)
Limit values	For heavy metals, sometimes a comparison with threshold values proposed in the sewage sludge regulation.
Additional information	
Survey on soil management	No
Gaps/weaknesses identified in soil monitoring	Diversity of labs (and methods) and sampling strategies and sampling protocols
Recommendations for future/ needs on harmonization	The definition of common data standards to favour data exchanges (between private Labs and INRAE (GIS Sol))
Data availability	Only with permission of the Labs
Website	https://www.gissol.fr/le-gis/programmes/base-de-donnees-danalyses-des-terres-bdat-62

Soil monitoring – Spain – case study 2.1

Sub-category	Information collected
General information	
Project/initiative name	National inventory of Soil Health (Inventario Nacional de Salud del Suelo; MITECO-TRAGSA)
Description of monitoring	
Land use type	All types
Scale	National scale
Level of implementation	Planned but not started
Frequency of monitoring	To be defined
Type of threat monitored	All soil threats (erosion, organic carbon loss, nutrient imbalance, acidification, contamination, sealing, compaction, salinization, loss of soil biofiversity)
Sampling strategy	To be defined
Sampling density	To be defined
Indicators	
Mission indicators	To be defined
Additional indicators	Under evaluation
Methods applied	direct measurements, models, etc., specific method to be defined
Limit values	---
Additional information	
Survey on soil management	---
Gaps/weaknesses identified in soil monitoring	---
Recommendations for future/ needs on harmonization	---
Data availability	Freely (expected)
Website	under construction

Soil monitoring – Spain – case study 2.2

Sub-category	Information collected
General information	
Project/initiative name	National Strategy to Combat Desertification (Estrategia Nacional de Lucha contra la Desertificación, ENLD)
Description of monitoring	
Land use type	natural - forest
Scale	National, regional scale
Level of implementation	implemented
Frequency of monitoring	Repeated over time
Type of threat monitored	desertification
Sampling strategy	---
Sampling density	---
Indicators	
Mission indicators	Vegetation cover
Additional indicators	---
Methods applied	Literature review
Limit values	---
Additional information	
Survey on soil management	---
Gaps/weaknesses identified in soil monitoring	---
Recommendations for future/ needs on harmonization	---
Data availability	Freely
Website	https://www.miteco.gob.es/es/biodiversidad/temas/desertificacion-restauracion/estrategia_nacional_lucha_desertificacion_web_2022_tcm30-542085.pdf

Soil monitoring – Spain – case study 2.3

Sub-category	Information collected
General information	
Project/initiative name	Environmental Profile of Spain (PAE)
Description of monitoring	
Land use type	All
Scale	National
Level of implementation	implemented
Frequency of monitoring	Repeated over time
Type of threat monitored	Soil erosion; soil organic carbon loss; loss of soil biodiversity; soil sealing
Sampling strategy	(2) The INES is taken on a continual and cyclical basis every 10 years. It is divided into five sections according to the various types of erosion: sheet and rill erosion, gully erosion, deep erosion, riverbed erosion and wind erosion.
Sampling density	---
Indicators	
Mission indicators	soil structure including soil bulk density and absence of soil sealing and erosion; landscape heterogeneity
Additional indicators	(1) Variation on urban soil and building plots surfaces; (2) Soil loss by erosion processes
Methods applied	GIS; direct measurement (1) Information recovery; (2) "Soil loss by erosion processes" indicator shows the annual soil loss due to sheet, rill and gully erosion calculated by the INES using the Revised Universal Soil Loss Equation (RUSLE) model. It is measured in t/ha with respect to the total geographical area of each autonomous community.
Limit values	(1) Reference values (In the indicator, 'Moderate' soil loss is defined as 0–10 t/ha/year, 'Intermediate' as 10–25 t/ha/year, and 'High' as over 25 t/ha/year.)
Additional information	
Survey on soil management	No
Data availability	Freely
Website	https://www.miteco.gob.es/en/ministerio/servicios/informacion/indicadores-ambientales/indice_perfil_ambiental.aspx

Soil monitoring – Spain – case study 2.4

Sub-category	Information collected
General information	
Project/initiative name	National Soil Erosion Inventory (Inventario Nacional de Erosión de Suelos)
Description of monitoring	
Land use type	All
Scale	National, regional scale
Level of implementation	implemented
Frequency of monitoring	Periodically (10 years)
Type of threat monitored	Soil erosion;
Sampling strategy	---
Sampling density	---
Indicators	
Mission indicators	soil structure including soil bulk density and absence of soil sealing and erosion;
Additional indicators	Soil loss by erosion
Methods applied	GIS "Soil loss by erosion processes" indicator shows the annual soil loss due to sheet, rill and gully erosion calculated by the INES using the RUSLE model. It is measured in t/ha with respect to the total geographical area of each autonomous community.
Limit values	---
Additional information	
Survey on soil management	No
Gaps/weaknesses identified in soil monitoring	---
Recommendations for future/ needs on harmonization	---
Data availability	Freely
Website	https://www.miteco.gob.es/en/biodiversidad/temas/inventarios-nacionales/inventario-nacional-erosion-suelos/Descarga_INES.aspx

Soil monitoring – Spain – case study 2.5

Sub-category	Information collected
General information	
Project/initiative name	Environmental Information Network of Andalusia (Red de Información Ambiental de Andalucía, REDIAM) + Informe de Medio Ambiente en Andalucía (IMA)
Description of monitoring	
Land use type	All
Scale	Regional (Andalucia)
Level of implementation	implemented
Frequency of monitoring	Repeated over time
Type of threat monitored	Soil erosion; Soil contamination; soil organic carbon loss; loss of soil biodiversity; soil sealing
Sampling strategy	---
Sampling density	---
Indicators	
Mission indicators	soil structure including soil bulk density and absence of soil sealing and erosion; landscape heterogeneity; presence of soil pollutants
Additional indicators	Soil loss evolution; soil use change; soil contamination
Methods applied	GIS; direct measurement Soil Loss Equation (RUSLE) model. It is measured in t/ha with respect to the total geographical area of each autonomous community.
Limit values	Tm/ha/y: low: (0,12]; medium: (12,50]; high: (50,100]; very high: >100
Additional information	
Data availability	Freely
Website	https://www.juntadeandalucia.es/medioambiente/portal/acceso-rediam/indicadores-ambientales/2022 https://portalrediam.cica.es/descargas?path=%2F05_CALIDAD_AMBIENTAL%2F03_RESIDUOS_SUELOS%2F04_SUELOS_CONTAMINADOS

Soil monitoring – Spain – case study 2.6

Sub-category	Information collected
General information	
Project/initiative name	SIOSE (Information System on Land Occupation in Spain), under the National Plan for Territory Observation (PNOT)
Description of monitoring	
Land use type	All
Scale	National scale
Level of implementation	implemented
Frequency of monitoring	Repeated over time
Type of threat monitored	---
Sampling strategy	Periodically, at surface level
Sampling density	---
Indicators	
Mission indicators	---
Additional indicators	Land Occupation
Methods applied	GIS;
Limit values	---
Additional information	
Survey on soil management	---
Gaps/weaknesses identified in soil monitoring	This indicator by itself is not providing direct measure of soil health. But it may combine with other strategies providing value.
Recommendations for future/ needs on harmonization	---
Data availability	Freely
Website	http://www.siose.es/presentacion

Kvadratnettet monitoring – Denmark – case study 3

I: Project ID and objective

Project details	
Name and acronym:	Agricultural Soil Sampling Grid (Kvadratnettet/The Square Grid)
Funding programme:	Different fundings The monitoring is managed by SEGES Innovation (en.seges.dk))
Countries involved:	Denmark
Project duration *(start year and end year):*	Established in 1985 and still ongoing

Project main objective:
The Agricultural Soil Sampling Grid in Denmark was established in 1985 based on a 7 x 7 km^2 grid to monitor the nitrogen content in the soil on a national basis. When the grid was established soil sampling was carried out in 25 cm intervals down to 1 meter depth. In total 820 sites were sampled. 608 of these were on **agricultural land**, 55 on **perennial grassland**, 46 in **deciduous forest**, 60 in **conifer forest**, 16 on **heathland**, 5 on **wet natural land** and 30 on other land (Østergaard and Mamsen, 1990).

The points are mainly used for measuring the content of mineral nitrogen, but a part of the points have also been revisited to analyse the content of carbon as well as phosphorus. The data set on soil carbon measurements was established over a period spanning 22 years, i.e. with soil sampling and analytical campaigns in 1986-1987, 1997-1998, and 2009-2010. A common procedure of soil sampling and analyses was followed as far as possible but included technological developments and changes of analytical equipment between 1986 and 2010. Data from 1986-1987 and 1997-1998 has been published by Heidmann et al. (2001) and the new data of carbon is described by Taghizadeh-Toosi et al. (2014b). For simplicity, the years of sampling and analyses are in the following referred to by the starting year of the campaigns, i.e., 1986, 1997, 2009, and 2018.

II: Monitoring level considered:

- The grid is national (7 x 7 km^2). Total of 820 points

III: Indicators addressed in soil monitoring described in the project

Mission indicators:

- soil organic carbon stock or content;
- soil bulk density
- soil nutrients mineral nitrogen
- vegetation cover (*diversity of vegetation cover*);
- Soil water retention

How soil health/quality indicators are estimated

Organic and total carbon after dry combustion (ISO 10694:1995)

Dry bulk density (ISO 11272;2017)

Total P was determined by wet oxidation in a mixture of concentrated perchloric and sulphuric acid. Bicarbonate extractable P (Olsen P) was analysed according to Banderis et al. (1976). Oxalate extractable Al, Fe and P were determined by ICP-OES (Inductively Coupled Plasma Optical Emission Spectrometry) after extraction with acid ammonium oxalate (Schwertmann, 1964) and the degree of P saturation (DPS) was calculated as the ratio between the molar concentrations of P and half the sum of Al and Fe in soils.

Nitrogen: Dumas Total N

Soil water retention (ISO 11274:2019)

The model C-TOOL, which is a robust soil organic carbon (SOC) model that can simulate the major trends in the C content of Danish agricultural mineral soils down to 1 m depth, has been used to model long term trends (Taghizadeh-Toosi 2014a).

Short summary of monitoring described in the project

Monitoring procedure is described by Gyldenkærne and Frederiksen (2015) and Heidmann et al. (2001).

Soil sampling and C analyses in 1986

In 1986, soil samples were collected from 590 grid areas (50 x 50 m^2) located on **agricultural** soils in the Agricultural Soil Sampling Grid. At each grid area sampling were made at four soil depths; 0–25, 25–50, 50-75 and 75-100 cm. The depths were selected to represent the plough layer (0–25 cm), the main rooting zone (0–50 cm) and the drainage depth (~100 cm). Sixteen soil cores were sampled within each grid area by following three parallel lines across the area. For each grid area and soil depth the 16 samples were mixed into one homogeneous bulk sample. Soil types of the grid points were classified according to the Danish Texture Classification System (JB No 1-12). Most points were located in JB1-7 soils. Only 7 points were located in JB8-12 soils. The soil samples were analysed for C and N. Information on soil use and management (crop rotations, fertilisation etc.) during the period was available from the Agricultural Advisory Centre and allows an analysis of the impact of soil management on the development in soil C- and N-content.

Soil sampling and P and C analyses in 1997

In 1997, soil samples were collected from 445 grid areas (50 x 50 m^2) that were retrieved according to 4 cm soil maps (i.e., within 20-40 m from the 1986 sampling areas). The sampling protocol was identical to the sampling in 1986, but only carbon contents were measured. Total carbon (TC) content was determined by IR analysis of the amount of CO_2 produced after combustion. TC was interpreted as total organic carbon (TOC) unless a precedent effervescence test indicated the presence of inorganic carbonates. If inorganic carbonates (IC) were present, IC was determined and TOC was calculated as the difference between TOC and IC.

The phosphorus content and the degree of phosphorus saturation in acid oxalate (DPS) for grid points of 337 **agricultural soil** profiles and 32 soil profiles from **deciduous forests** sampled at 0–0.25, 0.25–0.50, 0.50–0.75 and 0.75–1.00 m were reported by Rubæk et al. (2013). Changes in soil P content between 1987 and 1998 at 0–0.25 and 0.25–0.50 m were also examined in 337 and 335 agricultural grid points, respectively.

Soil sampling and C analyses in 2009/10

In 2009, 504 grid points were retrieved and marked out using current GPS technology with a precision of ≈ 0.5 m. The retrieved 50 x 50 m^2 grid areas were subdivided in 100 grid cells of 5 by 5 m^2 and 16 of these grid cells (selected randomly a priori) were used for soil sampling to 1 m depth with division into three depth intervals, 0-25, 25-50 and 50-100 cm as described above.

During all C analyses (i.e., both in 1986, 1997 and 2009) four control soils stored in the air-dry state were routinely included to ensure the quality of the analyses. Typically, one control soil sample was included for every ten samples. The quality of the analyses was accepted if the measured C content of the four control soil remained within their respective ranges of 0.57-0.64, 1.06-1.12, 1.40-1.54 and 2.66-3.24 %C.

Further, to qualify the reproducibility of the sampling strategy and the analytical methods, two tests were performed during 2009. Firstly, the soil sampling at 40 of the grid areas was repeated, but at 16 other grid cells (selected randomly a priori) than in the original sampling. These samples were treated and analysed as described above, including separation in the three depth intervals (i.e., n = 120). This test was done to evaluate the role of small-scale variation for the resulting C data. Secondly, 151 individual soil samples (randomly selected among grid areas and soil depths) were subjected to reanalysis in the laboratory using the same methodology as described above to evaluate the role of analytical variation for the resulting TOC data.

Soil sampling and C analyses in 2018

In 2018, 148 grid points were sampled and analysed for mineral nitrogen in the topsoil. Measurements were supplemented by model calculation in order to establish a nitrogen forecast for 2018. The results were compared with the average nitrogen content measured in the period between 2007 and 2017.
(https://www.landbrugsinfo.dk/public/f/2/f/godskning_kvalstofprognosen_2018).

IV: Was soil monitoring accompanied by any surveys on soil management?

For each grid point, the farmer was interviewed each year on the land use and management. This information was categorised into the following land 60 use and crop classes: 1) Grass, 2) Autumn sown cereals and rapeseed with straw removed, 3) Autumn sown cereals and rapeseed with straw incorporated, 4) Spring sown cereals, rapeseed and maize with straw removed, 5) Spring sown cereals, rapeseed and maize with straw incorporation, and 6) Spring sown row crops. For the crop management the following options were used: 1) Main crop followed by cover crop or under sown grass, 2) Soil ploughed, 3) Cattle manure applied, 4) Pig manure applied, and 5) Application of other type of organic material for fertilisation.

IX: Additional information

Publications

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- Østergaard, H.S. & Mamsen, P., 1990: Kvadratnet for nitratundersøgelser i Danmark, Oversigt 1986-1989. Landbrugets Rådgivningscenter, Landskontoret for Planteavl, April 1990, pp 75.

Soil monitoring – Poland – case study 4

Sub-category	Information collected
General information	
Project/initiative name	Monitoring Chemizmu Gleb Ornych Polski (Monitoring of the chemistry of arable soils in Poland)
Description of monitoring	
Land use type	Agricultural
Scale	National scale
Level of implementation	implemented
Frequency of monitoring	From 1995, repeated every 5 years
Type of threat monitored	Soil organic carbon loss; Nutrient imbalance; Soil acidification; Soil contamination
Sampling strategy	Soil samples are collected from the 0 – 20 cm soil layer every 5 years
Sampling density	216 permanent control points located throughout the country are collected and analysed at 5-year intervals; sites are georeferenced (precision depends on GPS devices) and a composite sample is taken from an area of 100 m^2 (square 10 x 10 m, 20 subsamples collected)
Indicators	
Mission indicators	Presence of soil pollutants (trace elements, PAHs), Soil organic carbon content Soil nutrients (N, P, K, Ca, micronutrients) and acidity (pH) Vegetation cover
Additional indicators	Mineral nitrogen content (N-NH4, N-NO3); total and available sulphur; chloroorganic pesticides (DDT, linden, aldrin, endrin, deldrin, a-HCH, b-HCH, g-HCH (only in 2015);
Methods applied	In general, according the same methodology described in monitoring database.
Limit values	Reference values are used for 12 trace elements, 10 individual PAHs, and chloroorganic pesticides
Additional information	
Survey on soil management	In place of soil sampling the vegetation cover (type of crops) is identified.
Gaps/weaknesses identified in soil monitoring	Emerging contaminants and loss of biodiversity are not included in the soil monitoring.
Recommendations for future/ needs on harmonization	---
Data availability	Freely
Website	https://www.gios.gov.pl/chemizm_gleb/

Soil monitoring – Norway – case study 5.1

I: Project ID and objective

Project details	
Name and acronym:	Soil and water monitoring programme in agriculture **JOVA**
Funding programme:	Norwegian Department of Agriculture and Food
Countries involved:	Norway
Project duration *(start year and end year)*:	*1992 - constantly continued*

Project main objective:
The Norwegian Agricultural Environmental Monitoring Programme (JOVA) is a national programme for soil and water monitoring in agriculture dominated catchments in Norway. The catchments represent the most important agricultural areas in the country with regard to climate, soil and management practices. JOVA was initiated in 1992 with the aim to document the effects of agricultural practices and measures on runoff and water quality. In total 13 catchments are monitored. In most of them there is a continuous record of water-flow and sampling for analysis of nutrients, particles and pesticides. During the monitoring period, JOVA has established a database with long time-series of data for nutrient runoff, soil erosion, pesticide loss and agricultural management practices. Objectives to document the levels of losses of suspended sediments (SS) and nutrients in different parts of Norway and from different agricultural production systems and evaluate the effects of political strategies on these losses.

II: Monitoring level considered *(please indicate appropriate from the list below)*

- **farm scale**
- **regional inside a country**
- **national**

III: Indicators addressed in soil monitoring described in the project

Mission indicators *:*

- **presence of soil pollutants, excess nutrients and salts***;*
  - ***trace elements,***
  - ***organic pollutants*** *(e.g.,* ***pesticides****)*
- **soil organic carbon stock or content**;
- **soil structure including soil bulk density and absence of soil sealing and erosion;**
- **soil nutrients and acidity (pH)** ***(essential nutrients: N, P, K, S, Ca; micronutrients)*****;**

IX: Additional information

WEBSITE:https://www.nibio.no/en/subjects/environment/the-norwegian-agricultural-environmental-monitoring-programme-jova

Soil monitoring – Norway – case study 5.2

I: Project ID and objective

Project details	
Name and acronym:	Norwegian soil monitoring programme in forests and grazing lands
Funding programme:	The Norwegian Ministry of Agriculture and Food is funding the programme.
Countries involved:	Norway
Project duration *(start year and end year):*	first decade (2023–2032) next decade (2033–2042)

Project main objective:
National Monitoring of Soil Organic Carbon (SOC) addresses the national monitoring of soil organic carbon (SOC) in forests and grasslands, which is scheduled to occur over two 10-year cycles. This monitoring program is designed to enhance Norway's greenhouse gas inventory and establish essential research infrastructure. Its primary goal is to improve the evaluation of model-based estimates used for reporting land use and forestry under the United Nations Framework Convention on Climate Change. The project focuses on emphasizing the significance of carbon storage in the soil of boreal forests. It highlights that the soil in these forests stores two to three times more carbon than the atmosphere. The project aims to raise awareness about the balance between the supply and decomposition of organic materials in the soil, a key factor in determining the amount of carbon stored.

II: Monitoring level considered:

- **regional inside a country**
- **national**

III: Indicators addressed in soil monitoring described in the project

Mission indicators:

- **soil organic carbon stock or content**;
- **soil structure including soil bulk density and absence of soil sealing and erosion**;
- **soil nutrients and acidity (pH)** ***(essential nutrients: N, P, K, S, Ca; micronutrients)*;**
- **landscape heterogeneity** *(**forestry, grassland**)*;
- **forest cover** ***(area of forests, area of wooded lands, share of non-native tree species)***

How soil health/quality indicators are estimated

Samples will be taken from all plots in the intensive grasslands category (approximately 300 sample plots) and a systematic selection of plots in forests (approx. 3,000 sample plots).

This will take place over two 10-year cycles with the annual collection of samples in intensive grassland and forest from approximately 30 and 300 sample plots respectively. That means that during the first decade (2023–2032), the first round of samples will be taken from all plots, and during the next decade (2033–2042), the sampling will be repeated in order to obtain figures relating to changes.

Other indicators *:*
This work should help to improve the Norwegian greenhouse gas inventory over time, and the data will be essential for evaluating the model-based estimates that are currently used for reporting land use and land-use change and forestry (LULUCF) under the United Nations Framework Convention on Climate Change (UNFCCC).

Short summary of monitoring described in the project:
frequency of sampling: This will take place over two 10-year cycles with the annual collection of samples in intensive grassland and forest.

IX: Additional information

WEBSITE: https://www.nibio.no/en/subjects/soil/monitoring-soil-organic-carbon-in-forests-and-grasslands/national-soil-organic-carbon-monitoring--now-were-getting-started

Soil monitoring – Norway – case study 5.3

I: Project ID and objective

Project details	
Name and acronym:	Norwegian soil monitoring programme for soil health (JordVAAK)
Funding programme:	Norwegian Department of Agriculture and Food
Countries involved:	Norway
Project duration *(start year and end year):*	2023 - constantly continued

Project main objective:
The implementation of a monitoring programme for soil health in Norway was adopted by the parties in the Agricultural Settlement in 2022. The soil monitoring system will represent Norwegian **arable land**, i.e., cultivated soil, surface cultivated soil and infield pasture land. Under Norwegian Monitoring Programme a range of indicators that describe the condition of the soil on the agricultural will be assessed with special relevance to the main threats to Norwegian soils: erosion, loss of organic matter, loss of biodiversity, soil compaction and contamination.
The main aim of establishing a soil monitoring system in Norway is to obtain information about the condition of Norwegian soil and its development for domestic use. Such updated information is a prerequisite for implementing measures and giving advice on agronomic practice in order to deal with the challenges as described by the IPC.

II: Monitoring level considered:

- **farm scale**
- **regional inside a country**
- **national**

III: Indicators addressed in soil monitoring described in the project

Mission indicators:

- **presence of soil pollutants**,
- **soil organic carbon stock or content**;
- **soil structure including soil bulk density and absence of soil sealing and erosion**;
- **soil biodiversity**;

How soil health/quality indicators are estimated
Measurement methods will be established in the future for indicators selected to assess five main threats (erosion, loss of organic matter, loss of biodiversity, soil compaction and contamination)

Short summary of monitoring described in the project:

- *frequency of sampling* will depend on the indicators selected to monitor the main threats. According to initial approach for monitoring purposes, the country will be divided into three monitoring regions: Northern, Central and Southern. In these regions, a total of 1,000 random locations will be selected at least two kilometres apart.

IX: Additional information

WEBSITE: https://www.nibio.no/en/news/national-monitoring-programme-for-soil-health

https://www.nibio.no/en/projects/enhancement-of-sustainable-land-soil-resource-management-in-agriculture-e2soilagri/jordvaak--implementation-of-the-norwegian-agricultural-soil-monitoring-programme