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Towards climate-smart sustainable management of agricultural soils

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Stocktaking for Agricultural Soil Quality and Ecosystem Services Indicators and their Reference Values (SIREN)

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ABSTRACT

The SIREN project has made an inventory of indicator systems for assessing soil quality and ecosystem services derived from agricultural soils, as currently used by Member States associated in the EJP SOIL program and beyond. The project aimed to identify and review the national approaches to make use of soil data in the assessment of soil-related ecosystem services, and has surveyed the knowledge gaps and needs for development hindering policy implementation as experienced in the 20 countries participating in the SIREN consortium. A comprehensive conceptual framework linking soil quality to ecosystem services has been collated from earlier proposals in the scientific literature, unifying various concepts associated with soil quality and ecosystem services, and providing a glossary of consistent terminology. SIREN has also taken stock of evaluation criteria for indicators of soil quality as implemented in national soil monitoring schemes. Based on reviews of literature, international policy, international stakeholder views, wide application in national soil monitoring and application in EU projects contributing to agricultural soil quality assessment, a synthesis was produced of policy-relevant soil quality indicators with high potential for harmonised application in national and European monitoring. A tiered approach is proposed for implementation of such a minimum dataset.

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Author contributions to this report are indicated *suo loco* by authorship over the chapters and sections.

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LIST OF ACRONYMS AND ABBREVIATIONS

EEA	European Environment Agency
EPF	Ecological Production Function
ES	Ecosystem services
EU	European Union
MAES	Mapping and Assessment of Ecosystems and their Services
MS	Member States associated to EJP SOIL and part of the SIREN consortium, also “Partners”
NEA	National Ecosystem Assessment
NCA	Natural Capital Assessment
PTF	Pedotransfer function
SH	Soil Health
SOM	Soil organic matter
SQ	Soil Quality
SQI	Soil Quality Indicators
WP	EJP SOIL program Work Package

HEADLINES

1. SIREN provides a consistent glossary and conceptual framework linking the concepts of SQ and ES

2. SIREN reviewed policy-relevancy of SQIs and evaluation criteria in terms of implementation in national SQ and ES monitoring schemes, body of scientific literature and application in EU projects, and the need as called for by specific international policy areas involving soil quality.

3. SIREN identifies knowledge gaps and immediate needs for development towards policy implementation and governance, as signalled by the participating EJP SOIL MS.

4. SIREN results emphasize the need for stakeholder participation in the development of national (and European) monitoring schemes, to assure acceptance and practicability in soil management. Knowledge transfer, capacity building, and development and integration of SQ and ES monitoring is urgently needed in most EJP SOIL Member States.

5. SIREN comes with proposals for limited harmonisation of national SQ monitoring schemes in a tiered approach, to facilitate pan-European evaluation of environmental condition against the Green Deal policy objectives.

EXECUTIVE SUMMARY

Soils are rapidly becoming a focal point for integrated environmental policy. The European Commission's proposal for a renewed EU Soil Strategy is anchored in the EU's 2030 Biodiversity Strategy, in the Climate Adaptation Strategy and in the EU Action Plan, and envisages that by 2050 all soil ecosystems in the EU will be in a healthy state and be protected. It rests on three pillars of the Green Deal: climate, biodiversity and circular economy. The Commission has therefore launched the coordination of soil policy as the fourth pillar to achieve healthy terrestrial and aquatic ecosystems through better soil and water management, including across borders. Part of the soil policy involves the objective that 70% of agricultural soils are under sustainable management by 2030, which will need to be evaluated on the basis of nationally established monitoring systems for soil health. Because soils are now recognised as a crucial environmental compartment in the pursuit of a range of very ambitious policy objectives, the European understanding of concept of soil quality is currently evolving from the more traditional foci on soil fertility and soil contamination towards a broader inclusion of soil functions and ecosystem services, both in view of combating soil threats and in pushing forward sustainable land management. National soil monitoring schemes and evaluation criteria will need inclusive development along this course, not only to facilitate future policy evaluation, but also to support the development of innovative management practices and to inform governance regarding economic incentives for sustainable land use.

The SIREN project has been carried out as a priority in the EJP SOIL Roadmap to establish an inventory of evaluation frameworks for ecosystem services and soil quality in use in Europe and of the associated knowledge and development needs. The project also was aimed take stock of desirable values and associated target values of soil quality indicators and identification of the knowledge needs for pedoclimatic and agricultural system contexts.

Stocktaking of soil data use and evaluation in ES assessment

The SIREN consortium has taken stock amongst the associated EJP SOIL Partners of the use of soil data in the assessment of ecosystem services, and of the implementation of evaluation criteria for soil quality indicator data in monitoring schemes predominantly at the national scale. Where performed by Partners, ES assessment serves either of two purposes: to assess, at a national scale, the status and functioning of ecosystems under environmental change, or to inform decision-making in spatial planning or payments for services. For the majority of Partners, soils are theoretically taken into account in these ES assessments by characterising soil functions. Soil Quality data are poorly specified in National Ecosystem Assessment reports, however, and evaluated by unclearly documented modelling approaches or expert judgement.

The use of soil quality indicator (SQI) monitoring data to assess soil functions and ES is not widely distributed across the participating EJP SOIL MS. Those countries who do use Soil Quality indicator data generally use ES classification based on CICES, or a modification thereof. The largest commonality in SQIs implemented between MS is for parameters to quantify soil organic carbon (stocks and changes). A clear omission for almost all MS relates to soil biological parameters, addressing soil biodiversity either with respect to structural aspects (species richness, etc.), or functional aspects (associated with soil functions and provision of ES), or both. SQIs for water regulation and organic contaminants are also implemented by few MS.

The ES concept has been incorporated in policy by few MS only, and only for a limited number of ES - never for an integrated full range as e.g. classified by CICES. The challenges that hinder policy implementation are diverse and highly variable among MS. Top common priorities are the development and enforcement of national soil monitoring program in MS where such program does not exist or are deemed insufficient for ES assessment, the development of national ES assessment using SQI data, and the identification of references and target values to interpret ES assessments.

National evaluation criteria for soil quality indicators such as references and target values have been implemented scarcely, and primarily concern soil contaminants or nutrient contents in association to allowable fertilisation quota, rather than soil functions relating to ES provision. Particularly, no reference values exist for soil organic carbon stocks and sequestering (except for 'no decline').

A key knowledge gap shared by most Partners is the selection and development of indicators that are fit for purpose (translatable to targeted ES) and robust (sufficient background data, variability understood), and the quantification of the relationship between SQIs and associated ES. Also, the contextualisation of evaluation criteria by soil type, land use, climate zone, or management practices is a widely recognised research priority.
In terms of governance, a limited structuring and coordination of soil monitoring between government bodies and academia is hampering integrated and effective data acquisition and assessment. Capacity building and financial resourcing was also considered limited by many Partners.

Framework linking Soil Quality and Ecosystem Services

Terminology and definitions are different, and misunderstanding, miscommunication and segregation by schools of thought have slowed down cooperative development between the science realms of 'soil quality' (originally natural sciences) and that of 'ecosystem services' (originally socio- and environmental economics). Based on review of scientific literature and feedback from consortium Partners' on an earlier draft, SIREN has collated a conceptual framework linking soil quality to ecosystem services, featuring a consistent glossary of key terminology from environmental and socio-economic sciences.

As defined by the Soil Mission reports (Veerman et al. 2020, Giuffré et al. 2021), the European understanding of 'soil quality' appears to be developing towards a broader inclusion of soil functioning, and a wide array of ES provision with no increases in trade-offs, in the interest of an inclusive society. Observing that a range of definitions exists in the literature and amongst the MS, we consider that the concepts of soil quality and soil health need to be defined with a wide scope, integrating across land uses and soil functions, before being narrowed down for application in particular situations, for specific stakeholders and objectives (which in itself may justify specifically focused selections of fit-for-purpose indicators).

A general need for development towards policy implementation of the soil health and ecosystem approaches will require further integration of environmental policies, with consolidation of common concepts and frameworks, and harmonisation and synchronisation of monitoring in time and space, and between governance levels.
To use soil data in a harmonised assessment of ES at European level, the relationships between soil functions and ES need to be quantified under a harmonised conceptual framework and standardised terminology, and using a common classification of ES. The CICES classification system seems most appealing, but has been elaborated to specific requirements by many MS, and should be elaborated to become more inclusive for soils.

Towards harmonised pan-European SQ monitoring

First of all, it showed from the inventory amongst EJP SOIL MS that there is substantial support for harmonisation of SQ monitoring in Europe. This is expected to help "levelling the playing field" by stimulating the scientific exchange and capacity building across MS, as well as some standardisation in indicator selection. However, where some partners plead for simple, low-cost and replicable soil indicators, others support the use of complex and integrated indicators. Simplicity and pragmatism seem key to success, however, for short-term harmonisation of a first generation of SQIs for national and pan-European monitoring of SQ. Moreover, a fifth of the MS phrased conditions to a harmonised approach. Flexibility in the choice of methods and protocols for harmonised SQIs (i.e. limited standardisation) was motivated by the desire to be able to continue long-term measurement series. A possibility for differentiation of evaluation criteria by regional context was also a strongly expressed condition, reflecting that soils, climate and agricultural systems can differ significantly between countries and SQ assessment would therefore require references and target values for SQIs tailored at a national or EU region level. Instead of homology, an approach by *analogy* is recommended for harmonisation, where the programming of monitoring and basic indicators are agreed upon but the actual implementation of specific methods and their protocols to assess indicators is left open to MS with regard to specific needs and historical usage. A tiered approach may alleviate the problem of countries moving at different speeds, and with different levels of detail.

Indicator selection should be a top-down process where policy-relevant SQIs are selected to inform on predefined policy objectives, rather than a bottom-up process where SQIs are preselected on the basis of localised experience from historical use, cheap costs rather than cost-effectiveness, or -worst of all- scientific lobbyism. It can be concluded that process guidance on the optimalisation of SQI selection is needed, especially regarding national and pan-European applications.

Based on a compilation from literature review, application in EU projects, stakeholder needs, and inclusion in national regulations and soil monitoring schemes (EJP SOIL stocktakes), SIREN has evaluated a longlist of most policy-relevant SQ indicators for application in pan-European soil monitoring. The result is a shortlist of commonly applied parameters that can be considered a ”minimum dataset” for a first tier of harmonised SQ monitoring. This set, however, still lacks some essential indicators for soil biodiversity, water regulation, and organic contaminants; these could not be selected from the longlist in an objective way, mostly for lack of wide application in national soil monitoring schemes.

Need for stakeholder participation in the development of national monitoring schemes.

Given the large heterogeneity in specific land use and management next to climatic and edaphic conditions, as well as substantial differences in political and social conditions among European countries, there is need to include local and regional stakeholders in the development of national monitoring schemes, as they can help identifying the issues they face in their home regions (representativeness) and can contribute in a multi-actor approach to the implementation of sustainable land management practices by participatory planning and decision-making at the national level and lower scales of governance. There is need for dialogue and co-construction between research and practice, and some countries have already recognised so and engaged accordingly.

1. INTRODUCTION

Jack Faber, Isabelle Cousin, Antonio Bispo and Peter Kuikman

1.1. From Soil Quality to Ecosystem Services – State of the Art

Evidently, agricultural soils provide human society with the production of food, fibres and energy. In a broader sense, soils fulfil all kinds of natural functions that sustain life through supporting primary production and decomposition processes, regulating nutrient, carbon and water cycles, and controlling multiple ecosystem processes such as buffering, filtering, storage, and providing habitat for organisms. To characterise this essential multifunctionality of soils, the concept of soil quality (SQ) was developed (Karlen *et al.* 1997) to provide a rationale for evaluation and sustainable use of soils.

The ecosystem service approach (MA 2005, TEEB 2010, Díaz *et al.* 2015) aims at integrating natural and social systems, providing a more comprehensive approach for decision-making and management. Ecosystem services (ES) have, by definition, an anthropocentric focus: ES are the direct or indirect contributions from ecosystems to human welfare, and something can be considered an ecosystem service if direct or indirect human demand and beneficiaries can be identified (Haines-Young and Potschin 2013). As central components of ecosystems, soils are essential in the provision of ES (Figure 1), and ES associated to soils are numerous (Adhikari and Hartemink 2016, Keesstra *et al.* 2016, Jónsson and Davíðsdóttir 2016, Pereira *et al.* 2018, Paul *et al.* 2021). It should though be acknowledged that soils do not produce ES independently from the functioning of the whole ecosystem (Bouma 2014). However, many soil characteristics and processes essential to SQ are not considered in final ES as classified by CICES 5.1, but in "intermediary" ES alone (Haines-Young and Potschin 2018), a.k.a. 'supporting services' (MA 2005).

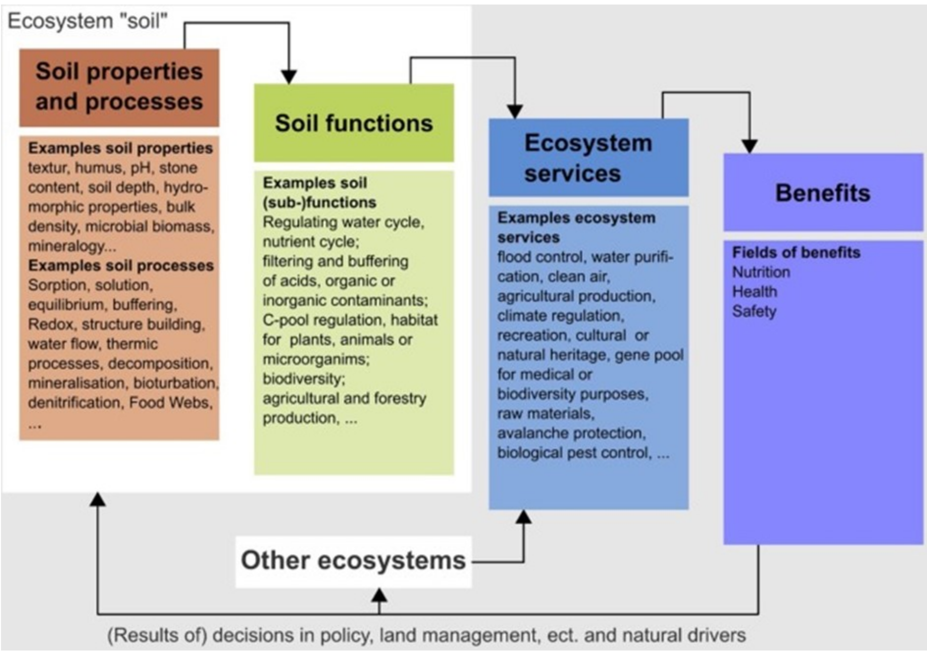

Figure 1. Contributions of soil functions to ecosystem services in the cascading framework developed by Haines-Young and Potschin (2008).

Also in terms of scale, there is an inherent discrepancy between indicators for SQ and indicators for ES provision, an ES approach requiring a broader spatial scale in terms of costs and benefits. Indeed, it has been stipulated that the earth-system approach and principles of the ecosystem supply chain are widely applicable to the ecosystems approach, and clarify where goods and services are really derived from (Robinson *et al.* 2013). A third potential discrepancy can be that indicators for SQ and ES may seem similar, but still refer to different quantities[1].

Soil data to inform policy

Information from soil and ES assessments, such as ES maps, has been given priority for spatial planning and decision making by government and non-governmental organizations (e.g., Egoh *et al.* 2008, Maes *et al.* 2012). The European Biodiversity Strategy of 2020 recognized ES mapping as a strategic action and the Member States were stimulated to map and assess the state of ecosystems and their services (Hauck *et al.* 2013, European Commission 2011). Globally, the UN Sustainable Development Goals and UN-FAO Global Soil Partnership value soil contribution to ES for environmental sustainability and human welfare. Adopting the concept of soil-related ES in policy making can be a powerful tool to evaluate a range of natural resources and environmental management strategies. Decision makers can evaluate the impact on the environment and on human well-being, and may develop management and policies that would benefit society and environment. Daily *et al.* (1997), Robinson *et al.* (2009), Bouma (2014), and Dominati *et al.* (2014) have highlighted a need for inclusion of ES and soil condition data in environmental policy and planning for societal benefits and environmental sustainability.

The actual capacity of soils to provide and sustain functions can be hampered by a number of degradation processes (Tóth *et al.* 2008, Schjønning *et al.* 2009, Stolte *et al.* 2016), identified as soil threats in the European Soil Thematic Strategy (EC 2006): (1) decline in organic matter, (2) soil erosion, (3) compaction, (4) salinisation, (5) landslides, (6) floods, (7) contamination and (8) sealing. Soil quality assessment and SQ monitoring have been largely focused on assessing soil degradation as a consequence of land use and the eight soil threats. Characteristically, common traditional objectives from the 1970's onwards have been to assess soil fertility of agricultural soils, and to assess environmental effects from chemicals at contaminated sites posing risks to public and environmental health. Over the last decades, SQ assessment has grown wider into other specific objectives (soil compaction, erosion, and loss of biodiversity) and have become more integrated to include all soil threats. This development has culminated in the (draft) EEA report establishing adequate indicators for each soil threat (Baritz *et al.* in prep). Basically, this approach in evaluating SQ is aimed at assessing negative aspects of soil degradation and provides a basis for soil protection, conservation and restoration. There can also be a second, complementary approach that is focused on the potential of soils to provide goods and services, even beyond the direct objectives of actual land owners and land managers (actors) but to the benefit of other stakeholders in society, elsewhere and perhaps later in time. This is the ES approach, and it is focused on the more positive aspects of enhancing the provision of such goods and services, but within restrictions of sustainable land use, i.e., in the long term sustaining the people, the planet and profits and prosperity. When developing and harmonizing indicators for agricultural soil monitoring against a background of the European Green Deal, it seems crucial to appreciate both approaches and develop a monitoring system that facilitates both.

Soil quality in terms of the capacity of a soil to contribute to the ecosystem provision of goods and services may be appreciated for 29 of 83 ES-classes in the CICES 5.1 classification that are soil-related (Paul *et al.* 2021). Notably, agricultural soil management may even affect the provision of 40 services

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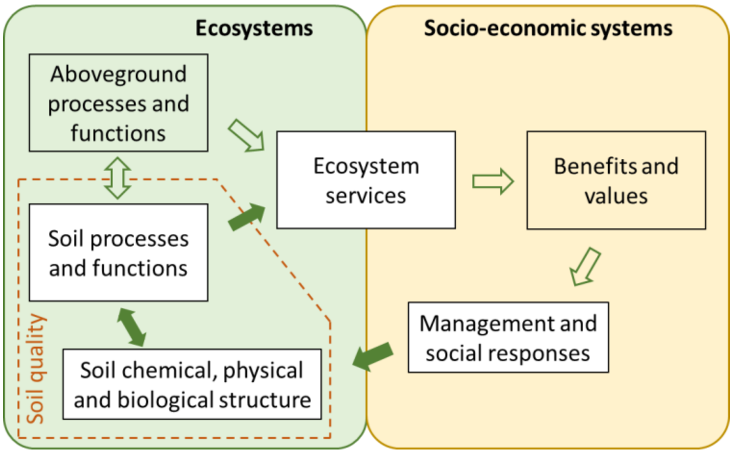
[1] For example: say the biomass of truffle mushrooms were used as a biological indicator for SQ, then the associated ES indicator would be the truffle biomass being harvested, which is usually less than the amount actually produced, but could increase with change in demand without change in SQ (disregarding the effect of increased digging on SQ).

(Paul *et al.* 2021) and agricultural land use is therefore a key driver in ES provision. Hence, to assess agricultural SQ in terms of provision of the entire array of soil-based ES, will require an equally extensive array of indicator parameters that can assess status and trends in the associated service providing units – be they of chemical, physical or biological nature. Without enumerating here in detail the 29 ES with their service-providing units (SPUs) and subsequently translating these to suitable soil parameters, it is obvious that any framework linking SQ to ES in this full complexity will hamper implementation in policy and management by the sheer complex nature of it. Simplicity and pragmatism therefore seem key to success.

1.2. Towards a dedicated framework

In the context of EJP SOIL, the ES approach is focused on agricultural soils, considered as a sub-component of a larger agricultural ecosystem (Figure 2). The structure of the soil ecosystem sub-component (including chemical, physical and biological aspects) sets the conditions for soil processes (structure interacting with function), resulting in the potential provision of soil-associated ES (and disservices) that can be benefited and valued by farmers and various other beneficiaries and stakeholders, directly or indirectly involved.



Original Draft
for use in Questionnaire
N.B. the final version is presented in section 3.2

Figure 2. Integrating the relationship between ecological (left, green) and socio-economic (right, yellow) systems for agricultural soils will provide a more comprehensive approach for evaluation and decision-making in policy and management (Adapted from Liquete et al. 2016). Highlighted boxes (white) and filled arrows (green) represent the focus of the SIREN study. Note: This scheme was drafted at the start of the project, and has been elaborated to more detail towards the end; a final version is presented in Chapter 3 Synthesis.

Soil ecosystem structure and the associated processes can be seen in mutual association to represent soil quality (SQ) which we tentatively defined, for use in the Questionnaire, as the capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health (adapted after Doran 1996, Karlen *et al.* 1997. Natural and anthropogenic factors can directly or indirectly cause change in agricultural production systems, inducing changes in management by farmers and other actors in the agricultural landscape (e.g., water boards, conservation managers), affecting the soil ecosystem functioning, and hence SQ including ES provision (Figure 3). SIREN aims to integrate Driver-Pressure-State-Impact-Response (DPSIR) and ES approaches into one single framework. This would facilitate development and implementation of integrated soil policy and land management.

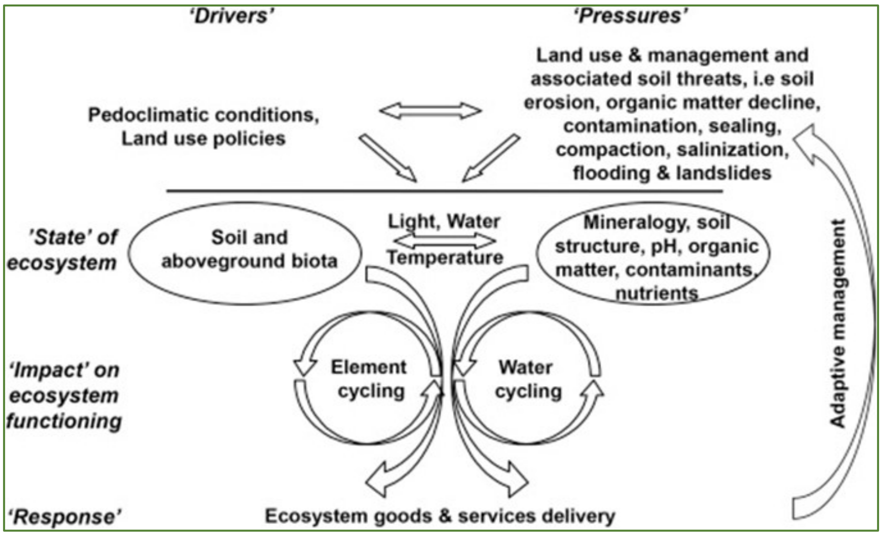


Figure 3. The Driver-Pressure-State-Impact-Response framework applied to soil (Bünemann et al. 2018).

1.3. Project Objectives

This project was conducted to stocktake the way how in Europe the status and functioning of agricultural soils and the provisioning of ES is being assessed and monitored by the countries of the EJP SOIL Partnership. The objectives of this stocktaking project are thus: i) to obtain an overview and synthesis of current scientific developments of indicators used in assessment of SQ and ES in agricultural landscapes in the literature and as implemented by consortium MS, ii) to record actual reference values of SQ and ES indicators implemented by the countries for specific indicators, in the different pedo-climatic conditions for the main agricultural production systems, iii) to assess how these indicators have been implemented in policy or land management practices across Europe, and iv) to contribute to EJP SOIL by providing reviewed and synthesised results as input for the updating of the Roadmap and WP3 research programming in the ES area.

Using literature and stocktaking to identify SQ indicators of soil properties, processes and functions in relation to the actual or potential delivery of ES, the SIREN project is after some simple questions:

- Can the same indicators be used, or what logic chains can be used to translate one into another?
- What information is missing to be able to do this translation?

SIREN has not aimed to accomplish mechanistic linkage to each and every soil-based ES, but rather established a principle to do so, should that be desired. The principle is illustrated as a process describing the knowledge needed to link soil structure and function to the provision of a particular ES.

1.4. Relevance

60-70% Of all soils in Europe are unhealthy, due to current management practices, pollution, urbanisation and the effects of climate change; the costs associated with soil degradation in the EU exceed 50 billion € per year (Veerman *et al.* 2020). Healthy soils are needed to bring success to the European Green Deal (Farm to Fork, Biodiversity, Forestry, Zero Pollution and Climate strategies). As a coordinated effort by the Commission in support of the Green Deal, the Mission on Soil Health and Food has renewed the European approach to soil health , and has proposed indicators for monitoring and assessment of soil health. Following the acceptance by the EC of the Mission's foresight on demand brief (Giuffré *et al.* 2021), the policy objective regarding these indicators is now that by 2030, at least 75% of all soils in each EU Member State are either healthy or show an improvement for all indicators where levels are below accepted thresholds, to support the provisioning of essential ecosystem services. This ambition clearly and urgently calls for the establishment and implementation of evaluation tools to structurally acquire data on soil condition and the provision of ecosystem services.

Across Europe, countries employ different approaches to acquire soil information and assess SQ and ES for the purpose of optimising land management[2]. A better understanding of these different approaches can i) reveal knowledge gaps for the expected impacts of EJP SOIL, ii) help establish stakeholder needs related to soil data and knowledge; iii) contribute to prioritization of the knowledge needs for further EJP SOIL research programming. Secondly, for political reasons (local or national environmental policies taking into account soils, or not), or scientific reasons (national definition of ES, access to or quality of soil data), countries may have developed either SQ indicators, or ES indicators, or both, and these may be related to one another, or not. By integrating SQ and ES indicators, SIREN is expected to cover a larger range of indicators related to soil state and functioning characteristics. Moreover, its overview and synthesis may contribute to establish commonalities in approaches for SQ and ES assessment across Europe with good potential for harmonisation in the longer term. Thirdly, and perhaps most importantly, frameworking SQ assessment into the wider scope of ES assessment may facilitate the integration of soil protection in different sectors of EU and national environmental policy, preparing the way to integrated legislation as called for by the first Soil Thematic Strategy.

1.5. Structure of the report

The 'pièce de résistance' of the report is the synthesis chapter 3, which contains condensed, highlighted and indeed integrated information from underlaying studies described in the consecutive chapters 4 and 5. First, in chapter 2 the structure and methodological approach of the SIREN project is described.

[2] Assessment schemes may involve three methodological approaches: (1) Indicator approaches using defined soil indicators derived from key chemical, physical and biological soil properties serving as simplified and one-dimensional proxies for soil functions or soil quality (Karlen *et al.* 2003, Wienhold *et al.* 2004, Obade and Lal 2016); (2) static approaches using simplified empirical rules (Lehmann *et al.* 2008, Calzolari *et al.* 2016); (3) dynamic approaches including soil processes, climate and other site-specific environmental factors as well as temporal and spatial variations in land use and land management practices (Vereecken *et al.* 2016).

2. PROJECT STRUCTURE AND RESEARCH APPROACH

Jack Faber

To accomplish the main objectives, SIREN has built on the results of the 2020 stocktake activity in T2.4.2 compiling indicator systems of SQ and ES across EU (Pavlů *et al.* 2021), and further deepened the understanding and synthesis by compiling relevant information in a follow-up stocktake amongst the participating EJP SOIL Partners. Note that SIREN adopted a broad definition of SQ, beyond the concept of Soil Fertility, and is embracing aspects of Soil Health (Kibblewhite *et al.* 2008) and acknowledging how SQ is used frequently in the literature, and in line with the preceding stocktake T2.4.2. It is assumed that this use of the term will enable to cover the broad range of interpretations as is likely used across Europe, and that it will enable unravelling all the concepts and frameworks in place.

SIREN aimed to establish a framework relating SQ indicators to soil function and ES (Task T1) (Figure 4), featuring logic chains that connect different levels of data aggregation and models to quantify these relationships; this includes concepts such as 'service providing units' (Luck *et al.* 2009) and 'ecological production functions' (Bruins *et al.* 2017). This framework has been synthesized from: i) general conceptual frameworks dedicated to evaluation of ES (Schwilch *et al.* 2015), especially the MAES conceptual framework (Maes *et al.* 2016) and its suggested list of indicators for use throughout Europe, and ii) frameworks more specifically dedicated to soils, like the approaches using the concept of Soil Natural Capital (Dominati *et al.* 2010) and stocks and fluxes evaluation (Robinson *et al.* 2009), and more recent operational propositions that can be used by stakeholders (Calzolari *et al.* 2016, Fossey *et al.* 2020).

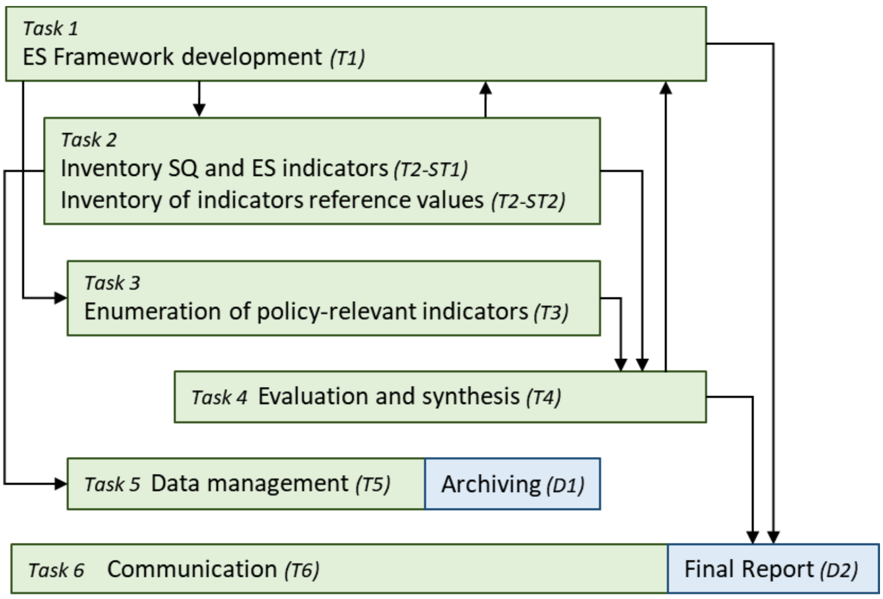


Figure 4. The SIREN workflow subdivided into Tasks leading to two deliverables: Questionnaire data for archiving with EJP SOIL WP6 (D1), and a report presenting review and synthesis of literature and stocktaken information (D2).

The framework helped formulating questions for the stocktake questionnaire (Task 2), addressing:
1) indicators for chemical, physical and biological status and processes in soil ('soil functions') and ES separately;
2) coverage of indicator systems for soil degradation, dealing with soil threats as recognised by EU

Soil Thematic Strategy;
3) European climate zones to recognise differences and commonalities, to evaluate potential for harmonisation.

All Partners were approached for background information on the national indicator systems concerning objectives and application (at national or lower spatial scales[3]) (Task T2-ST1), the needs and priorities for future assessment of ES by evaluation of soil indicators, and how these have been translated into policy implementation and land management in the participating country. In addition to stocktaking amongst the countries, desk studies were conducted with a focus on review papers, national ES assessments, Pan-European institutional approaches, and key European research projects, such as ENVASSO, LANDMARK, ISQAPER and MAES, to establish current views on best practices and perspectives for harmonisation and standardisation, and promising innovations (Task T3). Besides the SQ and ES indicators, the questionnaire was designed to help stocktaking the real (measured or modelled) values recorded and used in the countries of the SIREN consortium (Task T2-ST2). All SIREN Partners then answered the questionnaire, and the responses were reviewed and synthesized as part of Task T4.

Significant similarities as well as dissimilarities were anticipated among countries in the preference for particular indicators and associated reference values. The results of both stocktaking and literature review were synthesized (Task T4), aiming the synthesis to identify homologies and analogies in the various national approaches, and to establish specific and commonly shared knowledge gaps. Thus, SIREN derived research priorities for further programming in EJP SOIL, and identified and delivered opportunities to enhance harmonization across EU.

[3] Some MS conduct assessment at regional or lower scales because of specific conditions, as illustrated in the literature (Brenna *et al.* 2014, Fiorini *et al.* 2020). SIREN took stock of all scales in use, but focused the framework development on higher scales. It is recognised that better understanding is needed of thresholds (in scale and for contextual factors) relevant to the production of different ES (Andersson *et al.* 2015).

3. SYNTHESIS OF RESULTS

Recently, the EU presented a first European ecosystem assessment covering EU Member States and the UK. One key message was that the EU needs a better performing biodiversity observation network and more consistent ecosystem condition reporting (Maes *et al.* 2020). The SIREN project aimed to contribute to enhancing consistency, and in this synthesis chapter we bring together our findings regarding definitions and terminology, conceptual framework, policy-relevancy of indicators, and a proposal for harmonised implementation. We also identify major needs for development of knowledge, capacity building and governance towards policy development and evaluation with respect to ecosystem health, including soil health. We start with providing definitions and terminology as finalised at the end of the project (and which may to some extent differ from the initial versions as circulated via the Questionnaire).

3.1. Definitions for a consistent conceptual framework

Jack Faber, Antonio Bispo, Isabelle Cousin, David Montagne, Jan Bengtsson, Maria Viketoft

Even when everyone seems to speak the same language, a Babylonian confusion of tongues is close at hand. But clay tablets found in the region (Kroonenberg 2014) suggest that the construction of the Tower of Babel actually caused people to start speaking the same language, Aramaic.

Though not meant to reach Heaven in the literal sense, the global sustainability transition may be seen as the largest endeavour humankind as ever undertaken, requiring each person and every enterprise to participate. One of the first challenges then is clear communication.

Terminology and definitions are different between the science realms of ‘soil quality’ (natural sciences) and that of ‘ecosystem services’ (both natural sciences and socio- and environmental economics). Within these disciplines there are also different definitions across countries or policy areas, and even within countries the understanding of definitions used in science can be different from policy. For communication purposes, transparency and consistency, we provide our definitions as used in this report upfront. For the stocktaking activity itself, we tried approaching the Partners in an open and unbiased manner and we inquired for any specific national terminology and definitions in use, while providing our definitions as a default vocabulary.

Below we provide definitions for the most relevant concepts, as we have finalised at the end of the SIREN activities after many moments of learning and insight. As definitions can build upon one another, we present the concepts in some “logical” order, rather than alphabetically. Interestingly, when overviewing all definitions at once, an opportunity arises to put them in an order that facilitates consistency and clarity by framing in a larger conceptual framework (here: the SIREN framework), which is an emergent quality that is not embedded in a series of independent single item definitions as can be compiled from existing literature.

Indicator

The scientific understanding of indicators may differ from the policy view, where policy tends to approach soil quality indicators from an integrated higher level linked to a policy objective (*e.g.,* no decline in carbon content over time), and where science may rather focus on the directly measured variables or parameter(s) (e.g., actual value for loss on ignition in topsoil). In policy terms indicators are built on a hierarchy of soil parameters and may refer to specific soil functions at the level of ecosystem functioning and service provision. SIREN defines indicators as single or multiple parameters that are quantifiable using analytical protocols, or modelled integrated ‘scores’ based on interaction of such parameters, which are responsive to change in management and external drivers of soil quality. Indicators for ES may refer to other environmental compartments than soil as well.

Soil processes

Soil processes are the interactions among physical, chemical and biological soil components underlying soil functions and associated ecosystem services (*cf.* Haines-Young and Potschin 2008 and Fossey *et al.* 2020). These interactions are of biophysical, biochemical or physicochemical nature, and in combination make up the soil functions of cycling (decomposition, mineralization), storage (retention, buffering), soil formation, and transfer (filtering, release) of nutrients, contaminants, or water, as well as biotic support, and ultimately can be calculated to quantify the soil's contribution to ecosystem services. Examples are biochemical, enzymatic reactions such as ammonification and nitrification, contributing to nutrient cycling, or the biomechanical displacement of soil by soil macrofauna ('bioturbation'), or freezing-thawing cycles that reduce the stability of soil microaggregates.

Soil Functions

The term soil function is variably and confusingly used as a synonym for soil process, functioning, role, and service (Glenk *et al.* 2012, Baveye *et al.* 2016). In line with Bünemann *et al.* 2018 we define soil functions as (bundles of) soil processes that underpin the delivery of ecosystem services (e.g., the bundle of biochemical, biophysical and physicochemical processes regulating nutrient availability together contribute to the soil function 'Fertility', which underpins the ES of 'Decomposition and fixing processes') (Figure 5)[4]. Other examples of soil functions are: habitat provision (for roots, organisms), element cycling, decomposition, soil structure maintenance, biological population regulation, water cycling (infiltration, retention, percolation), and organic matter cycling (humus formation, C sequestration). Soil functions are the linkage from soil systems' processes to the valuation of performance or their services in the context of sustainable development (Giuffré *et al.* 2021). In this definition, soil functions are comparable to the potential provision of ecosystem services, consistent with the analogous concept of ecosystem function (de Groot *et al.* 2002); the nuanced difference is that soil functions are measured or modelled as process rates or quantities of functional groups, whereas the respective ES is the function expressed per surface area (hectares or a defined region) and time (year).

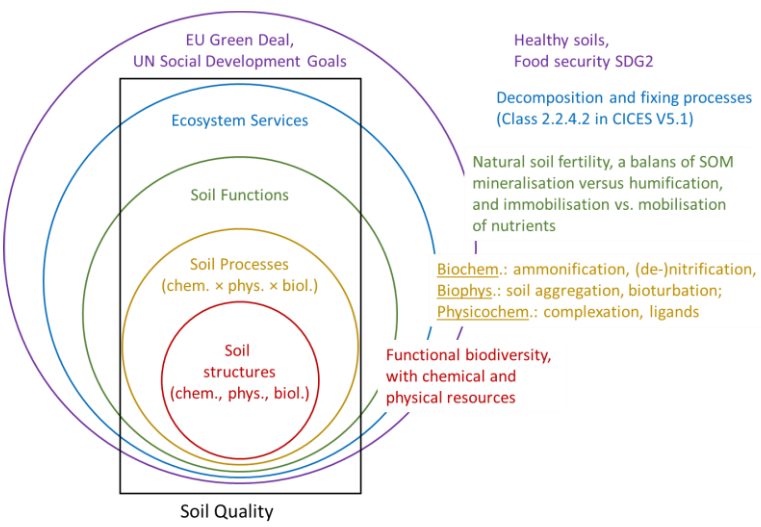


Figure 5. The hierarchy of soil quality parameters, simplified after Adhikari and Hartemink (2016) and illustrated with an example for evaluation of SDG2 policy-targeting on the basis of chemical, physical and biological indicators for soil structures and biochemical, biophysical and physicochemical processes that make up the soil function of natural fertility and the associated ES class 2.2.4.2 'Decomposition and fixing processes as recognised under CICES V5.1. Across this nested configuration Soil Quality can be seen as an integration of structural and functional aspects up to continued delivery of ecosystem services.

[4] Note that CICES V5.1. does not adequately detail classes of soil-derived ES, and there is some hierarchical mismatch as soil fertility also depends e.g. on soil structure, which is only indirectly accounted for in ES classes 'Control of erosion rates' (2.2.1.1) and 'Buffering and attenuation of mass movement' (2.2.1.2).

Ecosystem Approach

An ecosystem approach is a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way (Anon. 2000). Thus, the application of an ecosystem approach will help to reach a balance of the three objectives of the Convention on Biological Diversity: conservation, sustainable use, and the fair and equitable sharing of the benefits arising out of the utilization of genetic resources.

Ecosystem services

ES are defined as "*the direct and indirect contributions of an ecosystem to human well-being*" (TEEB, 2010). Most of the SIREN Partners acknowledge with this definition of ES, even if, as far as agricultural soils are concerned, some reference to crop quality is sometimes required. However, some Partners stated to move away from the ES concept and instead use the concept of Soil Natural Capital (see sections 4.2 and 4.5). Some suggestions for further development of the definition of ES are to clarify the role of human inputs (especially for agricultural ecosystems where the human capital is of prime importance), to improve our way of evaluation of soil-related ES on short and long terms, and to elaborate ES and healthy agricultural soils.

Nature's contributions to people (NCP)

NCP are all the contributions, both positive and negative, of living nature (diversity of organisms, ecosystems, and their associated ecological and evolutionary processes) to people's quality of life.[5] Introduced by IPBES (Pascual *et al.* 2017), the NCP concept is closely resembling the ES, but the NCP concept extends beyond the notion of ecosystem services by incorporating a more inclusive and interdisciplinary approach, particularly aiming to elaborate social aspects and cultural ecosystems (e.g. Daniel *et al.* 2012). Firstly, "*the unpacking and valuation of some cultural ecosystem services not readily amenable to biophysical or monetary metrics have lagged behind (Chan et al. 2012), and so has their mainstreaming into policy. In addition, as diverse disciplines and stakeholders remained at the margins, the initial scepticism toward the ecosystem services framework turned into active opposition, often based on the perceived risks of commodification of nature (Lele et al. 2013) and associated social equity concerns (Pascual et al. 2014)"* (quoted from Díaz *et al.* 2018). This claim by Diaz *et al.* (2018) has been challenged based on experiences in Europe, arguing that the science, policy and practice of ecosystem services have progressed much beyond a mere economic and ecological rationale (Maes *et al.* 2018). In the SIREN project we have not focussed much on cultural services and the social aspects, but we corroborate the absence of indicators of soil health that may help to establish social equity as part of sustainable land use.

Potential supply of ecosystem services

ES potential supply is the ecosystems' ability to generate services under current condition and type of use irrespective of demand for such services (Weber 2007, Villamagna *et al.* 2013, Hein *et al.* 2016).

It has been well established that harvests exceeding resource replacement rates reduce stocks essential for future supply in many places of the world (IPBES 2019). As with ecosystem capacity, potential supply also requires the supply to be sustainable, i.e., there should not be a reduction in the ability to supply the ecosystem service under consideration, or other services, when the service is supplied at the potential level. Potential supply can be considered synonymous to 'ecosystem function'.

Ecosystem service Flow

Ecosystem service flow is the part of the ES capacity that is directly or indirectly used or experienced by people. It is a function of the (agro)ecosystem type (e.g., arable or horticultural land, dairy

[5] IPBES Plenary 5 Decision IPBES-5/1: Implementation of the First Work Programme of the Platform, page 23; www.ipbes.net/event/ipbes-5-plenary

grassland), its biophysical setting and condition, and its accessibility and use by people (adapted from (Hein *et al.* 2016). It includes a spatial aspect, viz. the area representative for the end-users and beneficiaries that enjoy the benefit of the service. This typically is defined by the boundaries of the assessment area.

- The actual flow of ecosystem services in a given period does not have to be sustainable, i.e., it may be that the use of an ecosystem service is greater than that which can be generated in a sustainable manner over the long term. Over time, the use of ecosystem services beyond sustainable supply levels typically leads to ecosystem depletion and degradation. Based on MEA, *degradation* is interpreted as a change in ecosystem condition negatively affecting the ecosystem's structure, functioning, resilience and/or ability to provide ecosystem services. *Depletion* is more commonly interpreted as a reduction in a specific, harvested stock, as in depleting fish or timber stocks. Both degradation and depletion reflect changes in the ecosystem assets.
- Flows to people have been labelled 'final ecosystem services' whereas flows of services between ecosystems are often referred to as 'intermediate services' or 'intra-ecosystem flows' (UN 2016).
  Soil processes and 'soil functioning' have also be called supporting services, and may be considered as 'intermediary services' (Haines-Young and Potschin 2018). Typically, no direct beneficiaries can be recognised for intermediary services, hence these are discriminated from final services.
- For provisioning services, actual ecosystem service flow (e.g., crop or cow milk harvest) in a given period may be less than, equal to, or greater than the capacity (in the latter case an ecosystem can be expected to be subject to degradation). Capacity can only be greater than actual flow in cases where an increase in the use of an ecosystem service (compared to actual harvest levels) would not lead to a sustained, substantial decline in the availability of other ecosystem services.
- Regulating services result from ecosystem processes and functioning. A flow of these services may emerge from either naturally occurring processes independent of any human intervention (e.g., carbon sequestration in natural forests) or from deliberate interventions in the ecosystem (e.g., reforestation financed by a carbon project). Hein *et al.* (2016) assumed in both cases that capacity equals flow, since the use of a regulating service does not alter the ecosystem (even though modifying the ecosystem to enhance the supply of a regulating service may do so), making the use of a regulating service in principle always sustainable. For carbon sequestration, capacity also equals potential supply since the service is global (i.e., everybody benefits from this service regardless of where the sequestration takes place). For all other (non-global) regulating services, potential supply may be equal to or higher than flow and capacity.

Ecosystem Capacity

Ecosystem capacity is defined as the ability of an ecosystem to generate a service under current ecosystem condition and uses, at the highest yield or use level that does not negatively affect the future supply of the same or other ecosystem services from that ecosystem (Hein *et al.* 2016, and Figure 6).

Ecosystem capacity needs to be analysed for specific ecosystem services in recognition that capacities for each of these services are interlinked by synergies or trade-offs, and it should be possible to quantify capacity in both physical and monetary terms in order to understand ecosystems as assets. Capacity is defined independently from normative or historical baselines, or reference conditions.

Ecosystem Capability

Capability is an ecosystem's ability to *sustainably* generate a particular ecosystem service under current condition and type of use, and irrespective of potential impacts of increasing supply on the supply of other ecosystem services (after Hein et al. 2016, Figure 6).

An important restriction that applies to capability, capacity and potential supply is that they are assessed under current land cover and ecosystem use and composition, i.e., these concepts are analysed for the landscape or accounting area under its current ecosystem type.

Ecosystem health

or 'current ecosystem condition', is the ecosystem capacity measured for an ecosystem 'as it is now,' i.e., not in relation to what its condition might be under alternative situations. 'Condition' is used to indicate the state of the ecosystem in ecosystem accounting (UN *et al.* 2021).

- When all ecosystem services are used at a level below or equal to capacity, it is implied that the supply of services is, in theory, sustainable in perpetuity.
- Note that ecosystem services supply only materializes when there is demand for the service ('supply' and 'use' of the service can be equated). In the absence of a demand for a service, there is no exchange value for that service, and both service and capacity strictly do not exist. In Based on SQI data, however, the potential ES supply can nonetheless calculated to assess SH.

However, there is not a unique specification of ecosystem health. On the contrary, the concept can only be made concrete within the context of the desired values that a particular ecosystem or a particular landscape is supposed to provide (Kimmins, 2004). Here, stakeholders are key to contribute to specify the actual expectations to a soils' performance.

Soil Quality and Soil Health

Soil quality is the capacity of a soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain plant and animal productivity and health, maintain or enhance water and air quality, and to further provide ecosystem services on the long-term without (increased) trade-offs between ES (after Doran 1996, Karlen *et al.* 1997, and Giuffré *et al.* 2021).

The desired soil functions and the associated array of ES are preferably to be agreed between local authorities, actors and stakeholders, in order to come to a localised specification of essential aspects of soil quality (Kimmins 2004) that subsequently can then be measured for evaluation. Within the ecosystem and land-use boundaries the capacity of soils may be developed by adequate (sustainable) management practices to develop the provision of specific ES, or bundles of ES, (see 'ecosystem capacity'), but considering the principles of sustainable land use this should not lead to an increase in trade-offs to other ES, or to other people, elsewhere or later.

Soil Health is then derived from local SQ specifications, and is the actual (current) condition of the soil, as monitored and measured with dedicated indicators (which we traditionally still call SQIs)[6].

Thus, in terms of ES provision SQ associates with the *capacity* of the soil to provide the desired ES in potential, while SH associates with the current ecosystem *capability* and the actual supply of ES (Figure 6).

[6] This understanding of SH is different from what is encountered in most of USA literature and guidance for SH assessment, where the understanding of the concept is largely focussed on soil fertility with provision of a limited array of ES associated to agricultural production. The European approach appears to be developing towards a broader understanding of soil functioning, and a wide array of ES provision in the interest of the whole society (*cf.* Veerman *et al.* 2020, Giuffré *et al.* 2021).

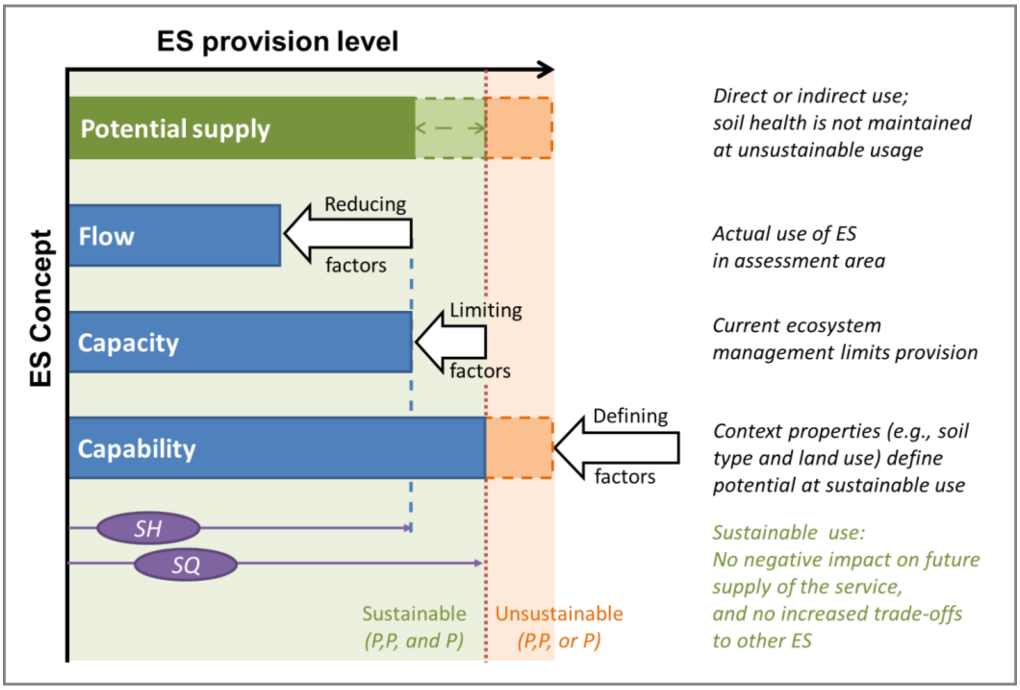


Figure 6. Graphical representation of soil quality and ecosystem service provision terminology against a theoretical borderline of sustainable use (People, Planet, Profit), illustrated for a single ES at a time (After Hein et al. 2016) with indication of delimiting factors (after Van Ittersum and Rabbinge 1997). Soil Health (SH) and Soil Quality (SQ) are drawn for comparison and differentiation, where SQ can be understood as equivalent to ecosystem capability, and SH is defined to equate the present ecosystem capacity (i.e., the potential supply of ES as the ecosystem condition is now).

An older definition of the SQ concept[7] was initially used in the SIREN proposal and Questionnaire. Discussions with Partners via the Questionnaire suggested that some improvements to the definition could be made. In addition, discussion with stakeholders and publications forthcoming during the project induced a further elaboration on the concepts of soil health and soil quality, as now provided above. Some suggestions remain to be reiterated below.

First, it was noted that this definition of Soil Quality not only applies to agricultural soils but extends to all soils irrespective of land use. We can also consider that a "whole" soil profile has to be considered for evaluation of its quality, while topsoil and subsoil horizons play differentiated parts in ecosystem functioning. Our framework applies to top soil as well as deeper layers. Other Partners suggested that SQ could feature explicit inclusion of economic benefit. We think that this would be better linked to the (e)valuation of soil-related ecosystem services, being dependent on local demand and appreciation of the services. Other suggestions from Partners included the idea that soil quality should perhaps enable the evaluation of resilience to climate change, and should incorporate the intrinsic value of life and biodiversity.

Bonfante *et al.* (2020) have proposed to focus soil health on actual soil conditions, as determined by a limited set of indicators that reflect favourable rooting conditions. In addition, soil quality can express inherent soil conditions in a given soil type (genoform), reflecting the effects of past and present soil management (expressed by various phenoforms). Likewise, American approaches to soil health also largely focus on aspects of soil fertility for agricultural production. We consider that the concepts of SQ and SH need to be defined at a wider scope, integrating across land uses and soil functions, before they can be narrowed down to application for particular situations, stakeholders and objectives (which then may require specific selections of fit-for-purpose SQIs).

[7] We preliminarily defined soil quality as the continued capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health (Doran 1996, Karlen *et al.* 1997).

Reference, or *Reference Value*

The reference is a value for an indicator representing its normal background value for defined local circumstances (ecological conditions), usually defined within the state boundaries of a country, and referring in general to a context of soil type, climatic zone and elevation, and land use and management. The term is equivalent to '*normal operating range*' (Kowalchuk *et al.* 2003) as used for biological indicators.

- Reference values for biological indicators can be associated to a particular combination of soil type and land use, e.g., arable land on sandy soil. A set of indicators with their respective reference values chosen at the optimal side of the normal operating range can then be combined into a comprehensive reference reflecting a good ecological status of the soil, within the boundaries set by the land use (Rutgers *et al.* 2007, 2008).
- References for chemical indicators can sometimes be standardised for soil type by correction factors involving clay and SOM fractions (e.g., for heavy metals).
- Reference values for naturally occurring elements and micro-nutrients (e.g., heavy metals, including non-essential elements) are not related to soil function or environmental risk.

Target Value

The target value represents the desired status for a particular indicator or set of indicators given specific ecological conditions, land use and objectives for use, by authorities and other stakeholders. It can be a minimum value or an optimum value, depending on the direction of development of SQ that is desired in the management objective.

- Target values can be related to specific risks ('soil threats') and/or specific soil functions, representing a threshold below or above which additional management or risk assessment is triggered. Threshold values are then sometimes defined.
- Target values can be specifically aimed at a particular objective (e.g., crop production), or may be 'integrated' across different objectives (policy or stakeholder), e.g., reflecting soil, water and climate policy goals, and/or ecosystem compartments soil-water-air.
- *Sustainable values* are targeted towards long-term usage within the *capability* boundaries (Hein *et al.* 2016) of the (agro)ecosystem, transcending beyond primary land use objectives to include other policy interests in a balanced way (the triple bottom line in "people, planet, prosperity"). Herein lies an aspect of scale of governance, as the sustainability bottom line for "planet" ultimately implies targets set globally, downscaled to the local level.

Natural Capital

Soil Natural capital is defined as a stock of natural assets yielding a flow of either natural resources or ecosystem services (Dominati *et al.* 2010, inspired by Costanza and Daly 1992). The Soil Natural Capital is then the chemical, physical and biological components of the soil usually defined as "properties" that generate, and are themselves affected by, the belowground processes. Some of them may be quite stable over time, the so-called "inherent properties" (for example clay mineralogy, rock fragments content), whereas other are under the strong influence of external drivers including climate and farming practices, the so-called ''manageable properties" (for example, pH, organic matter content, soil water content). NC includes natural resources such as gas, peat and coal; as these are non-renewable, they are not considered ES. Together with soil processes and functions, Soil Natural Capital underpins the potential supply of soil-related ecosystem services.

3.2. Final conceptual framework

Jack Faber, Loraine ten Damme, Isabelle Cousin

Below follows a brief narrative on the final version of the SIREN conceptual framework. It describes the linkage between ecological aspects of soil quality, how this cascades through ecosystem goods and services into benefits for people, society and institutions, how a direct feedback loop can affect ecosystem management via market-economic responses and policy incentives, and how external drivers and pressures –natural and anthropogenic – may change the agricultural system or its management. It has been elaborated from the preliminary version in the SIREN proposal (Figure 2), improved by a literature review, by feedbacks from the SIREN questionnaire, and from numerous discussions between project Partners and stakeholders.

Framework description

The SIREN conceptual framework is depicted as two interlinked boxes, representing the (agro-) ecosystem[8] and the socio-economic system (Figure 7). In the (agro-)ecosystems box, Soil Quality (SQ) is defined as the continued capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health (Doran 1996, Karlen *et al.* 1997). Soil quality is a reflection of the state of the soil's natural capital, i.e., the chemical, physical and biological structures of a soil that generate, and are themselves affected by, the belowground processes. Note that some natural characteristics, like the topography or the soil type, are inherently included in the Soil Natural Capital. As for other frameworks linking SQ and ES (see section 5.5.1), the SIREN framework distinguishes between soil processes, soil functions, and ES. The belowground processes together compose the soil functions, such as carbon sequestration, nutrient cycling, and water infiltration. Functions are quantified as process rates or densities of functional groups. Soil functions can be calculated to hectares and per year, to upscale them to the potential supply of ES. Note that ES also arise from aboveground ecosystem functions, and -importantly- the interaction between aboveground and belowground ecosystem components is an important system linkage. Also note that the SIREN framework makes no use of the concept of "intermediate ES", as this in the end is not needed to elaborate the relationship between SQ and ES, and may itself be a confusing term because ES are considered to be associated to beneficiaries, which intermediate services are not.

This supply of ES is a "potential" supply, and the actual use by society is often only partial. ES provision is typically represented as the flow of ("final") ES into benefits for people and institutions (as profited from and accordingly valued by specific stakeholders, or 'beneficiaries'). Specific demands in society may feed back into the management of (agro)ecosystems through socio-economic market mechanisms, and by policy and governance regulation and incentives (payment for ES, e.g., carbon credits). These societal demands potentially, and sometimes intentionally, affect the ecosystem as a whole as well as -although not necessarily- SQ and its natural capital. The extraction and actual use of goods (e.g., picking mushrooms) affect the natural assets that make up the natural capital.

Climate, invasive species and pests all influence the (agro-)ecosystem as natural drivers, limiting the suitability of certain agricultural practices and cropping systems and driving requirement of additional inputs as well as mitigating or adaptive measures (e.g., cultivars, irrigation, pesticides). The reverse arrow from (agro)ecosystems to natural drivers acknowledges the feedback/responsibility that farming may have on the occurrence of pests and invasive species. A bidirectional relation exists

[8] Note that, in the EJP SOIL context that is dedicated to agricultural soils, the SIREN framework has been developed for agro-ecosystems. Nevertheless, it would also apply for other ecosystems strongly influenced by human activities, like forest ecosystems for example.

between natural and anthropogenic drivers, acknowledging both a human influence (by society at large) on natural drivers as well as *vice versa* responsive behaviour of humans to the natural drivers.

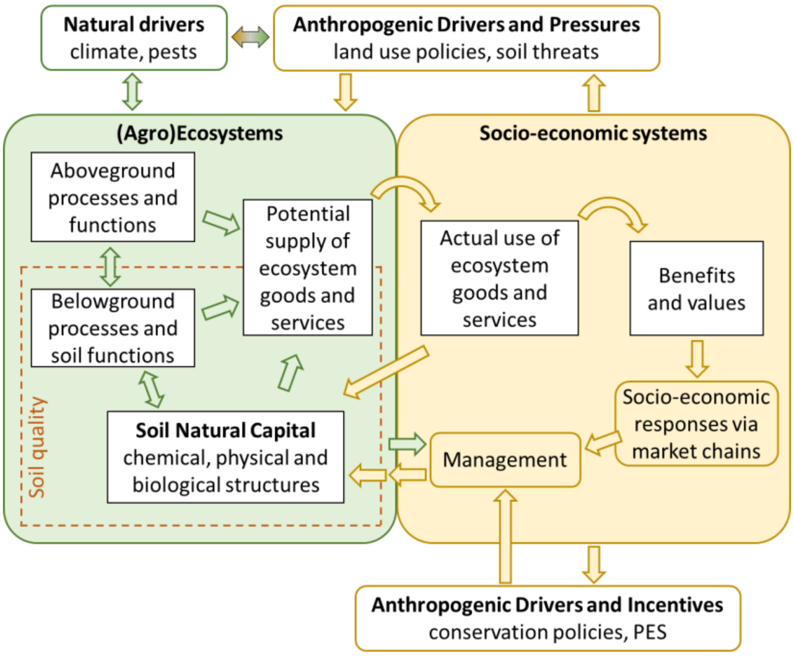


Figure 7. The SIREN framework integrates ecological (left, green) and socio-economic (right, yellow) systems, providing a comprehensively structured approach for evaluation and decision-making in policy and management regarding soil quality and ecosystem services. The square boxes in the framework are measurable/quantifiable, the rounded boxes are mechanistic forces from policy, management, market chains or natural drivers.

The socio-economic system leads to anthropogenic drivers of change that impact the (agro)ecosystem. The SIREN framework differentiates between direct anthropogenic drivers (usually positive), such as conservation and regeneration policies and payments for ES, and indirect anthropogenic drivers and pressures, soil threats and land use policies, the soil threats as recognised in the EU Soil Thematic Strategy. Land use policies can affect ecosystems both negatively as positively.

Linking SQ to ES

The potential supply of ES is key in linking SQ to ES provision, and it is crucial to understand the discrimination from actual flow of ES when using soil data in ES assessments, since soil data themselves do not inform about the actual flow of ES. In ES assessment as this is typically approached by socio-economic sciences, different data of a more socio-behavioural (e.g., 'willingness to pay') and economical nature are used to assess the actual use and flow in the region. But soil sciences can provide the tools to measure and model the condition of the soil ecosystem. This can be done in terms of the status and development of chemical, physical and biological structures (soil natural capital) and in terms of the rate of the associated soil processes and functions. In other words, soil sciences can provide suitable indicators for parameters that are considered mechanistically crucial for the associated ecosystem goods or services. These data can then be entered in simple or more intricate mathematical models (such as Ecological Production Functions (EPFs) and crop models) to calculate to provision of ES. This would, typically be *potential* supply, as no quantification of ES flow is involved.

Concepts linking functions to services

Ever since Dominati, Patterson and Mackay (2010) created a basis for analysing ES in relation to soils, an increasing body of literature dealing with the importance and conceptual integration of soils into the ES approach has been published. The subject has been discussed in relation to:

- soil functions (e.g., Adhikari and Hartemink 2016),
- soil threats (Schwilch *et al.* 2016),
- soils as natural capital (e.g., Robinson *et al.* 2009),
- institutional economics (Bartkowski *et al.* 2018),
- sustainable development goals (Keesstra *et al.* 2016) ,
- sustainability assessments (Helming *et al.* 2018).

ES are derived from soils and landscapes (leaving aquatic and marine environments out of scope here), and the spatial units producing those ES are termed 'service production areas' (Fisher *et al.* 2009) or also 'service-providing areas' (Syrbe and Walz 2012) (Figure 8). The chemical, physical and biological entities (structures) in those soils and landscapes are called 'service-providing units' (SPUs, *sensu* Luck *et al.*, 2003), as far as these ecological components are important in delivering the ES in the service-providing areas: chemical and physical entities with respect to abiotic ES, and biological entities regarding the biotic ES (CICES 5.1). The SPUs have a qualitative dimension, i.e., particular species or functional group(s) of species, or processes, as well as a quantitative dimension, i.e., what density, abundance or process rate is required to provide the service at the level required by the stakeholder(s) (Luck *et al.* 2009, Kontogianni *et al.* 2010). Being quantitative relationships, the EPFs as well as other models, can then mathematically relate the biophysicochemical structures and processes to the ecosystem functions (*sensu* de Groot *et al.* 2002) that drive ES delivery (Munns *et al.* 2015). Consequently, EPFs can be used to characterize the relationships between the condition of the ecosystem ('ecosystem health', *cf.* soil health), management practices and ES delivery (Heal 2000, Naidoo and Ricketts 2006).

EPFs can take on different shapes, ranging from a simple statistical association between measurement endpoint (e.g., SQ structure or function indicator) and ES provision, to a more mechanistic basis (Bruins *et al.* 2017; Faber *et al.* 2021), much alike dose-response relationships. Although our understanding of the relationship between land use, biodiversity and ES provision is limited (Nicholson *et al.* 2009), some patterns are emerging. For example, a recent systematic review of 13 ES produced a typology of links between ES and natural capital (Smith *et al.* 2017), identifying five pathways: amount of vegetation (related to air, soil and water regulation); provision of supporting habitat (related to pollination, pest regulation); presence of particular species, functional groups or traits (related to provisioning ES, species-based cultural services); biological and physical diversity (related to landscape-based cultural services); abiotic factors (related to water supply).

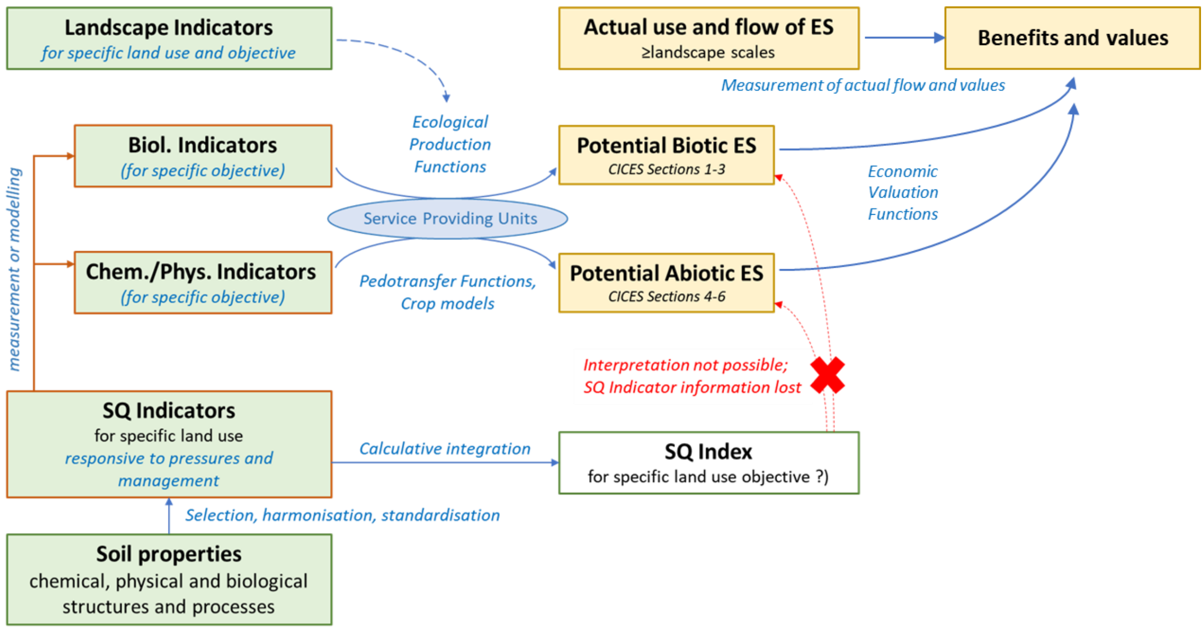


Figure 8. The establishment of logic chains using specific soil property data to assess the potential supply of ecosystem services "cascading" upwards by the selection of adequate soil (and landscape) quality indicators via measurement and calculus using ecological production functions and other models. Potential supplies can be valuated using economic valuation functions. Blue italic texts describe the selection, measurement and modelling activities involved in an ES assessment using soil data. A simple SQ index of composite indicators is often derived to inform policy by simple scoring, but may offer little information for ES assessment or responsive management.

Further development needs

Develop CICES to become soils and SQ inclusive

The implementation of the ES concept to assess the role of soils therein requires a standardised approach to indicator development. The Common International Classification of Ecosystem Services (CICES 5.1) of the European Environment Agency is a good basis for this *if* adapted to the specific requirements linked to soil-related services (Paul *et al.* 2021). Currently, the CICES system is little compatible with the current definition of SQ, being inclusive of a range of ES to be sustained by soils in good condition, whereas in the CICES V5.1 classification SQ is addressed by two classes of ES in the Regulation and Maintenance Section regarding the (biotic) regulation of soil quality: 'Weathering processes and their effect on soil quality' (code 2.2.4.1) and 'Decomposition and fixing processes and their effect on soil quality' (code 2.2.4.2). Paul *et al.* further highlighted a number of shortcomings and listed potential improvements, as well as a suggestion of standardization that may help in soil-related services assessments. Besides, only a third of the SIREN Partners does use the CICES to describe the relationships between soil functions and ES, and, as they use it, they do not distinguish between biotic and abiotic ES, despite the living /non-living constitution of soils. For the soil-related services, soil function assessment methods may be used to map levels of potential service supply. Paul *et al.* (2021) designed a list of soil management-related services to serve as a checklist to support the assessment of agricultural management options that affect soils and their effects on the potential supply of ES. In their approach, they specified the interrelation between properties and processes of soils and the changes resulting from land use and management, thereby facilitating sustainability assessment of land management practices. Standardization is instrumental in improving policy and management relevance of soil assessments, and to facilitate meta-analyses across geographic, climatic and management ranges.

Develop soil-based ES assessment from field to landscape scale

The contribution of soils to ES and thus human wellbeing appears best at the landscape scale. This is the scale where societal demands are confronted with the actual capacity for supply of ES, depending on land use and the intensity and quality of its management, and where social, economic and environmental aspects of soil management interact and conflict (Figure 7). The prominent role of the landscape has been acknowledged by the Horizon Europe Mission Board on Soil Health and Food, who in their interim report 'Caring for Soils is Caring for Life' complement the soil functions concept with a landscape perspective (Veerman *et al.* 2020).

Develop soil-based ES assessment from field to farm scale

To evaluate the effect of single management measures is common in scientific research as a reductionistic approach, but practical relevance can be fairly limited to the farming community. Farming systems are composed of an interlinked and interdependent complex of choices and measures that hardly can be changed, or not at all, without affecting one another. Also, quality certification compels farmers to accept entire systems of practices, rather than allowing for a stepwise or partial adoption of measures. Evaluation of agricultural measures in terms of sustainability should therefore address the farming system as a whole.

When following an ecosystem approach, revenues for the farmer in terms of farmgate prices should be assessed against their direct costs and investments, as the net income constitutes the local/regional success against the background of local/regional demands (for agricultural products *and* other ES), and subsidiary incentives may be determined accordingly in support of farmers' management for ES "for the greater good".

3.3. Policy relevancy and perspective for implementation

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Soil Quality (SQ) monitoring and assessment of ES are instruments that are useful in the evaluation of the state of the environment and to evaluate progress towards policy goals, e.g., regarding sustainable use of agricultural land. Part of the expected impact from the SIREN project is to contribute to a refined outline of the roadmap for research priorities, capacity building, and other objectives in the EJP SOIL program, related to soil quality assessment. This synthesis chapter will therefore identify key knowledge gaps and development needs as perceived in the MS and from scientific literature, including an assessment of feasibility and prioritization against the policy target deadlines. Here we first address some specific aspects of harmonisation of SQ monitoring, again synthesising from the stocktaking across EJP SOIL MS and literature, to optimise for national needs and capabilities, as well as scientific feasibility. First, we analyse where the major challenges lie regarding the development of national and European monitoring of soils and the assessment of ES.

The scope for SQ and ES assessment is set by needs, capacity and requirements from policy on the one side (i.e., "top down") versus from science on the other (i.e., "bottom up"). Science provides the conceptual and methodological means to provide adequate information to inform policy evaluation and decision-making but should do so in response to clearly defined outlines. Part of the discrepancy between the top-down and bottom-up approaches that has existed for some time is a lack of commonly perceived objectives and targets, which in turn is associated to a lack of common language. Other stakeholders, like farmers and their organizations, are becoming increasingly interested in, e.g., indicators for sustainable practices, and this will increase the need for clear communication. Most crucial in resolving this mismatch is to identify a common focus and understanding of 'good condition' of ecosystems against a background of 'sustainable management' of ecosystems, biodiversity, and natural capital. Stakeholders need to be involved early in the process (see the example, section 5.8.2) to ascertain acceptability and practicality of policy objectives and instrumentation.

Over the past decades, an almost bewildering variety of frameworks, indicators, and other concepts relating to SQ and soil-related ES has been produced in the scientific literature. This has raised awareness of the dependency of human well-being on soil quality, but has not led to implementation in major policy frameworks. The diversity in approaches and methodologies offered may have been confusing to policy- and decision-makers rather than attractive, lacking consistent support for immediate, specific and realistic use. We consider that the questions and needs identified by policy makers may not have been clearly articulated either. Ever since the Brundtland report "Our Common Future" (UN 1987), sustainable development has been on the international policy agenda, but the concept remains contested and vague. Policy demands have been diverse, at times inconsistent between policy sectors, i.e., unclear in terms of lack of integration, not defining 'good condition', and asking for an unarticulated single indicator for soil quality. But the situation is improving, now that, particularly at the global and EU level, policies are coming up with a clearer understanding of ecosystem health and good condition in terms of sustainable use, developing more concrete objectives. The UN SDGs, the European Green Deal (EC 2019) with core connections to the European Biodiversity Strategy (EC 2020a) and Farm to Fork Strategy (EC 2020b), all represent new, ambitious policies where the principles of sustainable use of the environment systematically apply. Strategic goals for climate neutrality, reversed biodiversity loss, and healthy food translate into e.g., 'no net carbon loss', 'no net loss of biodiversity and ecosystem services', cutting nutrient losses and reducing use and risk of chemical pesticides and instead aiming at increasing the provision and use of ES to maintain food production. Objectives that are articulated to such a degree are more readily translated by science into adequate toolkits, i.e., the selection of policy-relevant indicators with evaluation criteria to monitor states and trends towards the accomplishment of policy goals. Both UN and EU policies emphasize the need for an integrative approach with strong involvement of stakeholders. The Mission approach to the European Science and Innovation program, Horizon Europe 2021-2027 (EC 2021), reinforced this approach once more. So far and for some time now, only criteria and thresholds for water quality have been defined by the EU Water Framework Directive (EC 2000), the flagship environmental directive.
In the section on 'Reference setting for SQIs' we further describe the discourse on the "translation" of 'good condition' from policy into science. Also, the communication between science and policy is more direct through the Mission Boards and the joint programming of research and capacity building.

In addition to the described mismatch between policy and science in framing the objectives defining a good condition of the environment, there is a second major challenge towards development of European environmental monitoring, in particular soil monitoring. Structural evaluation of soil health across Europe in a context of sustainable land use would benefit from countries establishing monitoring schemes that share a common approach regarding indicators and evaluation criteria. This obviously requires MS and the EC to deal with the differences and commonalities that exist at the national level and between EU-zones. This seems difficult to overcome in a commonly agreed approach, unless some differences between countries are allowed for. Here too, top-down and bottom-up interests would benefit from clear understanding of commonly *shared* objectives and principles, to build pan-European SQ monitoring based on the *commonalities* in policy objectives and scientific approaches (rather than pursuing to resolve the intrinsic differences), and in response to stakeholder needs regarding freedom in management and income security.

Harmonisation

Developing a system of indicators and evaluation criteria is first of all severely challenged by the large heterogeneity of European soils and climates. There are 23 main soil types (Jones *et al.* 2005) and 13 pedoclimatic environmental zones with 84 strata (Metzger *et al.* 2005), not to mention the eight soil threats that are recognized to specifically impact soil quality at regional levels and focal areas across Europe (Huber *et al.* 2008, Tóth *et al.* 2008, Montanarella *et al.* 2018). These differences in environmental conditions and impacts, status and trends, requires specific responses to sustainably manage soil resources. Moreover, all these specific regions have specific land use and management, which adds the stakeholders into the equation, next to climatic and edaphic conditions. Since political and social conditions also vary substantially among European countries, there is also a need to include local and regional stakeholders in the process when developing indicators, as it is key that stakeholders recognize the issues they face in their regions (representativeness). Because of such differences in objectives and focus in national approaches to SQ assessment and monitoring, it would seem nearly impossible to organise soil monitoring in Europe in a completely harmonised and standardised manner. At least, given the diverse needs and views of the European countries, an approach to such harmonisation by the principle of homology in SQ monitoring requiring every country to use the *same* indicators and parameters, is likely to lack wide and committed support. Rather, instead of homology, an approach by *analogy* may be likely to receive better support, if the processes of monitoring and basic indicators are agreed upon but the actual implementation of specific methods and their protocols to assess indicators is left open to specific needs and historical usage between countries.

Thus, harmonisation of SQ monitoring is recommended to be sought in an agreement on the indicators to be used in national monitoring schemes, whilst leaving freedom to individual countries to implement their specific parameters and protocols of choice. Perhaps some further harmonisation could be realised amongst countries *within* EU zones, where the relatively larger similarities in environmental conditions, agronomic practices and problems could make harmonisation easier. A tiered approach may alleviate the problem of countries moving at different speeds, and with different levels of detail.

However, any limiting of harmonisation by the use of methods that are not standardised and commonly applied among countries would come at the expense of comparability of actual status *between* countries across Europe. By requiring that the same (or very similar) indicators are used while allowing for variation in the exact methods, it would still allow for comparability of trends over time and especially comparability *within* countries with existing long-term monitoring sequences that could be maintained. There is significant scientific value in that too, plus a political benefit of increased support from countries that are determined to continue their well-established and operationalised routines, often for historical and good reasons.

Higher tier indicators and methods are considered to feature even less harmonisation of methods, and instead allow for methods that provide more specific information according to individual needs in countries. Higher tier levels would result in better representing local or regional conditions and result in higher quality of the estimated impact of better support of indicator values. At these levels, it will also be natural to involve farmers and other stakeholders in the process of developing and improving indicators for SQ and ES like climate mitigation, which will profit greatly from indicators that are also applicable for individual farmers and landowners at the small scale where farmers recognize their site conditions and activities.

When it comes to harmonisation, it is not the place for science to advise on political and policy choices (and we may have overstepped this border already at this point), but we feel that the diversity in scientific methods amongst countries should not obstruct development and implementation of Europe-wide SQ monitoring methods, if consensus can be reached on the indicators that matter at large.

Perspective on SQ monitoring development

Harmonisation should be sought as much as possible in a 1st tier of EU-wide soil monitoring, with the national monitoring schemes feeding into EU-wide assessment of basic indicators. The selection of such indicators will follow from the commonalities in national objectives for monitoring and evaluation. At the national scale, most SQ monitoring schemes are currently aimed to either assess soil threats or at measuring SQ for agricultural purposes, but not for assessment of ES in general. Since scientific development to link soil data to ES assessment are still being developed, such indicators may mostly not expected to be delivered in the short term. It seems pragmatic to establish EU monitoring on the basis of existing national schemes, and thus accept to focus on the associated objectives linked to soil threats and single-function land use – however limited these are to evaluate sustainable land use at national levels. These schemes can be considered “low hanging fruits”, and can form the building material for a first, basic EU-wide approach and be evaluated for coverage of the key indicators to match EU policy goals. To this extent, the forthcoming report by the European Environmental Agency on SQ indicators and thresholds (EEA in prep. 2021) provides a sound review of the most relevant indicators with potential regarding the soil threats. As a second developmental need, national schemes would need elaboration to cover multiple land uses where applicable, and thirdly to be expanded towards assessment of soil-derived ES and soil natural capital.

A tiered approach to SQ monitoring in EU

A crucial question is whether SQIs in a low tier should already be feasible for application in ES assessment, now or in the future, or if data to that purpose should be derived where needed in higher tiers (by specific stakeholders, not EU). Clearly, for harmonised assessments across EU only 1st tier data may qualify, as this is the intended level of data for national reporting to EU. But this applies at best to assessment of *potential ES*, whereas actual use and flow of services is defined at local or regional scales, involving stakeholder demand, and thus will make use of local or regional data anyway. A tiered approach in data acquisition will bring about progressive understanding, if the consecutive tiers will make use of methods to produce linkable data. In other words, simple approaches in lower tiers should feed into more detailed and precise approaches in higher tiers. A basic question here is whether National Ecosystem Assessments should be comparable amongst countries, addressing the same ES? This is likely asking too much in terms of harmonisation and standardisation of SQIs... A pragmatic approach would again entail to review the currently applied indicators in terms of relevance for a range of most-relevant ES, and to harmonise the choice for such indicators in a 1st tier of SQ monitoring.

1st Tier SQIs: recommendation for a minimum dataset

In chapter 5 we compile a longlist of policy-relevant SQIs, based on review of international policies, implementation in national monitoring schemes by EJP SOIL MS, usage in scientific literature and European research projects, as well as stakeholder views (Table 1). Below, we present a charcoal-sketched shortlist of SQIs for implementation in a 1st tier of pan-European SQ monitoring, which we derived from that longlist by applying an objective selection procedure. This procedure was based on implementation by >50% of MS, and reflecting input from the Questionnaire and in-depth discussion with EEA. The selection procedure is described in more detail in section 5.10 and Table 13.

Table 1. Shortlist of indicators suggested as a minimum dataset for 1st Tier of harmonised soil quality monitoring across Europe.

Policy Indicator	Soil Quality Indicator
Soil physical condition	Texture, Porosity, Bulk density
Soil fertility	C concentration Total N P K pH
Erosion evaluation	Based on calculation
Salinity	Electric conductivity
Contamination	Heavy metal trace elements
Other contaminants	*Recommended to be included **
Soil biodiversity	
Water regulation	

** Based on our selection strategy, we observed significant omissions regarding indicators for soil biodiversity, organic contamination and water regulation/filtration. As soil condition data in these areas are called for by policies and stakeholders and (standardised as well as novel) methods are scientifically available, we recommend to also include relevant indicators in this 1st tier minimum dataset. Based on our stocktake and reviews it is yet impossible to select any without making subjective choices, which is what we wanted to avoid.*

Biological indicators missing most urgently

The importance of tracking, targeting and conserving soil biodiversity as a major component of overall terrestrial diversity is recognised both by the scientific community and policy makers. That soil biodiversity also contributes to important soil functions and the sustainability of soils, is also appreciated. However, at present biological indicators are lacking from SQ monitoring in most EJP SOIL MS. There is a need for contextual background data for referencing purposes, and biological SQIs are considered costly. On the other hand, a variety of biological indicators has been developed to an operational standard, and implementation in monitoring schemes would just be instrumental in generating such reference values. Biological indicators can also be considered to respond swiftly to changing conditions, and can be expected to be early responsive indicators of changes in soil health as biota are the mediators of soil processes. There is value to be gained from early information.

It should be recognised that biological indicators can inform biodiversity assessments (structural and functional aspects), or inform on the condition of the soil environment, e.g. in response to soil threats as by the use of bioindicators), which are different things. For purposes of biodiversity assessment (species richness, community structure, etc.) rare and endangered species may be listed for monitoring, but such species can be expected to have little impact on soil system functioning. On the other hand, monitoring key functional groups such as biomasses of fungi, bacteria and earthworms, provides little information on status and trends in soil structural biodiversity.

Other considerations

Whether SQIs included in a first tier only should be evaluated in top soil (0-20 (30) cm) or not, is also an important issue. In most on-going SQ monitoring programmes, only top-soil is sampled although the sub-soil is of importance for evaluation of e.g. soil carbon stocks. The approach of including sampling of deeper soil horizons is likely to be adopted by different countries in higher tiers.

Another important issue is knowledge about the distribution of soil types. Soil type can vary over short distances and sampling points in SQ monitoring need to represent the most relevant soil types in a 1st tier, while less relevant soil types may be addressed in later tiers. Land use again is an important criterion in the selection of sites for monitoring. The combination of soil type and land use crucially affects SQI values, and therefore evaluation criteria such as reference values need to be differentiated for this context. Climate zones also will induce such regional differentiation.

1st Tier SQIs: recommendation on method standardisation

The lack of harmonised routines is different for countries in which soil quality monitoring program is still under development. The development of new soil monitoring programs, frequently flagged as a gap and immediate need, could indeed benefit from the proposal of practical guidelines, including sampling and analytical methods, to monitor the set of the agreed basic indicators. Countries involved in the development of new soil monitoring program would then be free to select their practical procedures into such a harmonised toolbox. These guidelines could also be used to define a “common unit” for EU reporting on soil quality into which countries with a long history of soil quality monitoring could try to translate their own data using empirical relationships, when applicable. The adoption of either the common practices or the “common unit” through translation operations by an increasing number of European countries could over time increase the comparability of spatial trends between countries and across parts of the EU.

But as stated above, key is a harmonisation of indicators that answer to the policy needs, and the actual standardisation of methods and protocols would seem of secondary importance, if a consolidated monitoring across EU is to be established in the short term.

Reference setting for SQIs: from science to policy and back

In the MAES process two classes of agroecosystems have been recognised so far: cropland and grassland ecosystems (Maes *et al.* 2013). Cropland includes both intensively managed ecosystems and multifunctional areas supporting many semi- and natural species along with food production (lower intensity management and includes rotational cropping systems including grassland in rotations). Grassland includes intensively managed pastures for fodder production, and (semi-) natural (extensively managed) grasslands also referred to as pastures. With a focus on the EU level, this MAES typology is rough and broad, and some more detailed/different classifications at lower levels will need to be considered in the future, making distinction for land use intensity and sustainability and using parameters that relate to the farming system itself.

It will also be important to recognize that there is a difference between monitoring indicators in different land use classes and monitoring the agricultural (farming) systems at the farm level. For some ES, the farm or landscape is the appropriate scale to monitor, as the level of ES depends on land use patterns, and this may vary with the degree of land consolidation. Other aspects that need consideration are that crop rotations, their complexity and timing of e.g. semi-permanent crops in the sequences, may influence how and when to measure indicators of, for example, carbon sequestration, nutrient retention or organisms affecting soil structure. This also holds for farming methods like tilling or reduced tillage sequences. Many of the measures discussed in the Farm-to-Fork strategy will likely increase the complexity of crop rotations, as well as increase the year-to-year variation in crops, making many agricultural systems either more dynamic than presently, or less so by introducing more permanent crops. These changes are complicating monitoring of soils and will affect the precision in many monitoring programs, necessitating method development for dynamics of ES and soil quality.

Coming from the policy side a definition of ‘good condition’ for these agroecosystems is not available, except for (semi-)natural grasslands as covered by nature legislation (Habitats Directive). For cropland, very little legislation exists as a background for defining references for ecosystem condition (and thus for assessment of soil quality and ES provision). Yet, in view of international policy goals and strategies (including UN SDGs, EU Biodiversity Strategy and Fitness Check of the Nature Directives) and scientific identification of planetary boundaries (Steffen *et al.* 2015), the condition of agroecosystems has been defined as follows (EC *et al.* 2017):

Agroecosystems are modified ecosystems, they are in good condition when they support biodiversity, abiotic resources (soil-water-air) are not depleted, and they provide a balanced supply of ecosystem services (provisioning, regulating, cultural). Sustainable management is key to reaching or maintaining a good condition, with the aim to increase resilience and maintain the capacity of delivering services to current and future generations.

While this definition has been developed by EC, EEA, JRC, ETC/Biodiversity and ETC/ULS in unison, further elaboration is needed towards quantitative references or target values for both biotic and abiotic factors that determine ecosystem condition (here: soil quality), and this will encounter a number of challenges requiring further discussion to reach consensus:

- An agreed notion on balanced supply of ES (provisioning, regulating, cultural);
- An agreed notion of sustainable management practices;
- Long-term observations that can identify what is sustainable or non-sustainable management, validating no depletion of soil resources and biodiversity.

While a policy-based definition of evaluation criteria for monitoring the condition of the agroecosystem remains to be construed in terms of present sustainability principles, scientific approaches have been undertaken at a national level by some MS attempting to describe 'best conditions' under conventional practices.

3.4. Integrated knowledge gaps and needs for development

Chantal Hendriks, Katharina Meurer, Jack Faber

Using the categories developed based on the knowledge gaps extracted from the different sections (Table 2), we synthesise and define general conclusions and recommendations from the different Questionnaire sections A to D. Research and governance-related categories where most Partners indicated a knowledge gap is focussed on.

Questionnaire A - Conceptual framework

In section A, the Partners were specifically asked for the need for development of modelling linkages between SQI to assess ES and knowledge gaps that are perceived with respect to such ES modelling. The answers were categorized into those being more related to research and those directed towards policy implementation and governance.

In terms of research needs, it becomes clear that the largest needs relate to *Indicators development and quantification of SQ-ES relationships*. Besides the lack of research on the linkage between ES to soil data (as expressed by NL), the need for defining and developing a complete indicator for ES assessment exists (FR, LV). Moreover, Partners mentioned relationships between biological indicators and SOC dynamics (IE) or soil quality (IT, NO). Targeting a somewhat larger scale, linkages between SQI, carbon sequestration and climate change mitigation need to be found (SI). Furthermore, the relation of SQIs relating to cultural and supporting services are still considered to be under scientific development (SK). In terms of modelling approaches, substantial knowledge gaps in the translation of soil indicators to soil functions for proper model application was mentioned (IE).

Table 2.Classification of needs for knowledge development and implementation in policy and governance as harmonised across the Questionnaire Sections.

Sector	Knowledge gap, development need
Research	Development of conceptual framework, definitions
	Background data
	Assessment criteria
	Indicators, quantification of SQI-ES relationship
	Scenario studies soil type/land management
Policy and governance	Implement SQ Monitoring, integrate ES/NC assessment
	Harmonisation
	Coordinated knowledge implementation
	Policy development, regulations, incentives
	Communication, stakeholder participation
	Awareness raising, capacity building
	Policy evaluation

The needs for action on a higher, e.g. governmental, level was primarily directed towards *Harmonisation*. Overall, a common system for assessing the value of ES (BE), as well as a harmonized list of soil supporting services would be appreciated (FR). More specifically, parameters such as carbon content and soil texture, as well as methodologies for, e.g., erosion risk control should be harmonized at national and European scale (IT). In addition to that, models should be normalized and adapted for usage across countries (DK).

Questionnaire B - ES assessment based on SQ monitoring

The Partners were asked what, in their experience, is the biggest immediate knowledge gap hindering further development or policy implementation of ES assessment based on soil monitoring data. In terms of knowledge gaps related to research, most answers given by the consortium Partners (4 out of 7 Partners who answered that question) fell within the category *Development of conceptual frameworks and definitions*. Partners highlighted the need for the development of a better understanding or refinement of existing knowledge on key processes determining Soil Quality Indicators (SQIs) and ES (BE, DK). Indications on which processes and relationships are to be studied in more detail were given by only one Partner (FI). Suggestions to overcome this issue included non-experimental studies and field experiments (DK). Nevertheless, Norway highlighted that knowledge gaps persist regarding the practical implementation of improved management practices, making a clear link between research needs and governmental needs. For the latter, nine Partners answered in a way that suggests major efforts need to be related to *Implementation of SQ monitoring and ES/NC assessment, integrated in time and space*. Analysis of the answers provided by the individual Partners made clear that the needs regarding monitoring programs strongly differ, with some Partners expressing the general need for a structured monitoring program for soils (IE, LV, SK, and CH), while those with existing programs emphasize the need for continuation of cancelled programs (LT) or a stronger focus on smaller scales (farm, city, small region) (FR). One of the hurdles for assessment of ES using soil monitoring data – besides the financial aspect of establishing a corresponding program (SK) – is the lack of a nationally accepted conceptual framework on how to link specific soil data with soil functioning an ES (CH). However, even those MS that already have monitoring programs running indicated that those programs do not necessarily include SQIs and do not allow conclusions on ES either (SL, CH). One suggestion is the establishment of inter-disciplinary and inter-resort research projects focusing on ES (SK), which would allow supplementing existing (national) soil monitoring programs with missing SQI and influential site information for ES assessment (SL).

Questionnaire C - Referencing and targeting soil quality

In section C, Partners were asked to provide national evaluation criteria for soil quality indicators (SQI) and how reference and target values on soil quality link to ES.

Most frequently mentioned research knowledge gaps related to *'Research: indicators development, quantification of SQI-ES relationship*' (12 Partners). Within this category, five main knowledge gaps can be identified. Firstly, Partners lack knowledge on relationships between or the integration of SQI and ES (FR, LV, PT, CH). SQI are monitored selectively and fragmented over different ministries or programs, because monitoring schemes are often not set-up with the aim to relate them to ES. Secondly, Partners lack knowledge on the time and space frame at which SQI in relation to ES need to be monitored (IE). Thirdly, where Partners have SQI defined, indicators for assessing the status of ES are often lacking (BE-WA, LT, SP, UK). Fourthly, knowledge on the factors that influence relationships between SQI and ES are missing (FI, IE). The last knowledge gap is the lack in education on the importance of monitoring SQI in relation to ES (PL). Nine Partners indicated knowledge gaps related to 'Background data'. Notably, these Partners mentioned the same gaps: lack in SQ and ES indicators (FR, FI, PL), and lack in reference, target and/or threshold values (IE, LI, PL, PT, SK, SL, CH, UK).

Policy and governance related knowledge gaps are predominantly related to the *implementation and integration of soil quality monitoring* (7 Partners). The gaps include: the lack in political regulations on SQI monitoring (FR, NO, SE), lack in data or utilizing available data by governance institutes (FI, IE), progress on the conceptualization of ES by policy makers goes slow (SK), and the lack in integration of data and knowledge between ministries to link SQI to ES (CH). National (CH, CZ) and EU-wide (LV) harmonization of soil monitoring in relation to ES was indicated as a knowledge gap by only three Partners.

Questionnaire D - Policy relevance and implementation

Section D investigated whether policy and land management in the participating countries make use of ES assessments that are based on soil data. Additionally, current obstructions and challenges for implementation in policy were compiled.

By far, most research knowledge gaps fall within the category '*Indicators, quantification of SQ-ES relationship'* (13 MS). Within this category, many different gaps were mentioned by the Partners. Firstly, more research is needed to bridge the gap between SQI and ES (SL). Secondly, soil data is collected at different levels and using different methods to assess soil quality indicators (BE-FL). Consistency in the methodology is lacking. Thirdly, there is need for including SQ indicators in ES analysis (ES), and for collecting soil properties to map and assess ES in agricultural soils (instead of land cover and land cover changes) (PT). There is a need to identifying robust key indicators for soil quality (NO, PT, CH, IT). Where some partners plead for simple, low-cost and replicable soil indicators, others support the use of complex and integrated indicators. Fourthly, there is a need to assessing productive as well as non-productive functions (BE-WA). Fifthly, there is a gap in the differentiation of SQ and ES to soil threats (ES). The sixth research gap is on the quantification of SQI and ES (FR, PL, SK, CH). As CH stated: "not only the conceptual, but also the quantitative relationships between currently used indicators and soil functions as well as ES are generally under investigated. Therefore, establishing those relationships is of high priority and future studies should particularly address these quantitative linkages". The last gap mentioned in this category is a lack in detailed knowledge on the interactions that take place at the landscape scale (SP).

Policy and governance related knowledge gaps are dominantly (7 Partners) related to the category *'Implement and integrate SQ monitoring, NEA, NCA'*. Six Partners mentioned the lack in (financial) resources to initiate SQ and ES monitoring programs (BE-WA, FI, LV, LT, NO, SP). IE also mentioned the gap in spatial/temporal harmonization of monitoring schemes. As in section C, this section noted inconsistency in the systems used or approaches developed within a country or among national institutes (IT, LV) in the category 'Harmonization'.

In general

Overall, some knowledge gaps dominated the different sections. Harmonization is one of these frequently mentioned governmental knowledge gap. However, the scale at which Partners desire harmonization ranges from regional to European level. Besides, the elements in which harmonization is desired differs among Partners; e.g., soil data collection, soil monitoring schemes, modelling approach.

Even when Partners were able to fill in the database on SQIs and their reference/target/threshold values, a lack in soil quality or ES indicators (in particular, biological indicators) was indicated as a knowledge gap. Specifically, Partners missed the knowledge to link SQIs to ES and the (key) processes that influence this link. The SIREN conceptual framework can help bridging this gap, e.g. in the form of protocols, on how to derive soil functions from SQIs and how to assess ES from soil functions are needed.

The fragmentation of knowledge and data between ministries, research institutes and projects were another frequently mentioned knowledge gap. Due to this gap, data and knowledge exchange is suboptimal. Available data and knowledge should be utilized differently to make sure that data and knowledge generated by different ministries, institutes and projects are not lost, but bridged instead. When data and knowledge are bridged, overarching themes like ES can be pursued. We can conclude that Partners are at different development stages regarding ES assessment. Some do not collect any data on SQIs yet, while others collect SQI data but do not link these data to soil functions or ES yet. Consequently, the detail of individual knowledge gaps and needs varies strongly, depending on the status of monitoring programmes. All in all, most Partners do not yet make the connection between SQI and ES.

It became very clear that there is a strong gradient across countries depending on the status of their monitoring programmes and assessment of ES (Figure 9), and knowledge gaps that were indicated were strongly related to the level of progress. Partners that currently have no established monitoring programmes indicated a stronger need for better process understanding and a refinement of the existing knowledge on key processes Figure 9. Linkages of key needs for knowledge development, knowledge transfer and policy implementation that were indicated by Partners.(soil functions) determining SQIs and ES. Consequently, the process of setting up a monitoring programmes that allows for determination of "adequate" indicators and, in a next step, the assessment of ES, is still in early stages of development. This knowledge gap falls within the scope of the EJP SOIL Expected Impact 3, which is defined as "strengthening scientific capacities and cooperation across Europe including training of young scientist". The exchange between countries as to how ES assessments are set up and carried out is mandatory to deal with this need. However, this will very strongly strengthen the participation of individual countries in terms of data collection and contribution to scientific knowledge on a European level. Strongly related to that is the need for reference values and how to link these to ES, a knowledge gap that was identified primarily by countries without or in the early stages of ES assessment (using soil data). In addition to that, it was highlighted that stronger collaboration between research institutes and ministries is needed. The identified need for collaboration between research institutes implies that monitoring schemes may already be in place and specific indicators may already be measured, but that individual research institutions do not have access to that kind of data (or so far have not been aware of their existence). In order to better develop the assessment of ecosystem services, collaboration between institutions and monitoring schemes is essential. In addition, the importance of those monitoring schemes and assessments has to be better communicated to ministries, and support from higher instances is needed in order to keep schemes running at the national scale.

Overall, Partners agreed on the need for *harmonization*, but even here was a strong gradient: while countries without or with early-stage monitoring schemes wished for a better guideline on which indicators to sample and how they can be linked to ES, Partners with established monitoring indicated that the results should be harmonized on a larger scale in order to enable comparison across countries. However, a common need for compatibility of monitoring schemes and eventual analyses of collected parameters, e.g. using modelling, was expressed. With this, the expected impact EI4 of the EJP SOIL ("support harmonised European soil information, including for international reporting") is addressed. A common approach on ES assessment would further turn to EI5 on "fostering the uptake of soil management practices which are conducive to climate change adaptation and mitigation".

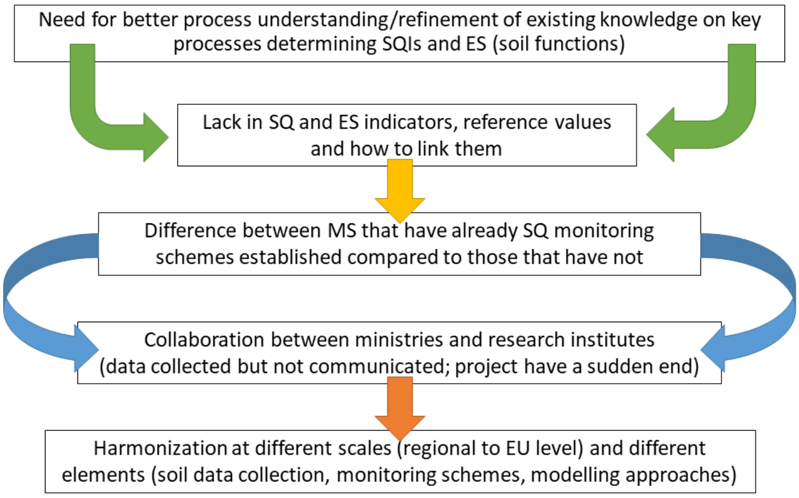


Figure 9. Linkages of key needs for knowledge development, knowledge transfer and policy implementation that were indicated by Partners.

3.5. General conclusions

Below follow the main conclusions as synthesized from the information obtained by the Questionnaire, and by review of scientific literature, EU projects, international policies and stakeholder interests.

1. To establish SQ monitoring in a setting of ecosystem health-focussed policies that ask for evaluation of soil-related ES and natural capital, the establishment of a commonly accepted comprehensive conceptual framework with related descriptive concepts and clear definitions is very much and urgently needed, both for scientific research and policy implementation.

As an outcome of the Soil Mission support, the importance to set a solid baseline with clear understanding/terminology and hierarchy regarding indicators and parameters was reiterated once more, as well as how the indicators and parameters relate to policy targets (Giuffré *et al.* 2021). SIREN aimed to provide in a comprehensive and consistent framework and terminology. We hope that our synthesis of various alternative scientific approaches, developed in the last decade, and nonetheless persisting needs for "clear and communicative" concepts amongst policymakers in individual countries and EU alike, is a helpful contribution.

2. Where performed by Partners, ES assessment serves either of two purposes: to assess, at a national scale, the status and functioning of ecosystems under environmental change, or to inform decision-making in spatial planning or payments for services. For the majority of Partners, soils are

theoretically taken into account in these ES assessments by characterising soil functions (or "soil quality" as a specific function). Soil Quality indicators are poorly specified in National Ecosystem Assessment reports, however, and evaluated by unclearly documented modelling approaches or expert judgement.

3. The use of soil quality indicator (SQI) monitoring data to assess soil functions and ES is not widely distributed across the participating EJP SOIL MS. Those countries who do use SQI data generally use ES classification based on CICES, or a modification thereof. The largest commonality in SQIs implemented between MS is related to parameters for soil organic carbon (stock, changes). A clear omission for almost all MS relates to soil biological parameters, addressing soil biodiversity either with respect to structural aspects (species richness, etc.), or functional aspects (associated with soil functions and provision of ES), or both. SQIs for water regulation and organic contaminants are also implemented by few MS.

4. The ES concept has been incorporated in policy by few MS only, and only for a limited number of ES -never for an integrated full range as e.g. classified by CICES. The challenges that hinder policy implementation are diverse and highly variable among MS. Top common priorities are the development and enforcement of national soil monitoring program in MS where such program does not exist or are deemed insufficient for ES assessment, the development of national ES assessment using SQI data, and the identification of references and target values to interpret ES assessments.

5. The implementation of biological indicators in national soil monitoring is scarce and insufficient to monitor status of structural biodiversity (e.g. species richness) and to assess functional aspects in the provision of ES. Indicators for soil water regulation and organic contaminants also lack representation in most countries' surveys.

Further major scientific knowledge gaps include the quantification of SQI-ES relationships (e.g. ecological production functions) and knowledge on the factors that influence these relationships, background data differentiating for EU regions, and guidance on the time and space frame at which SQI in relation to ES need to be monitored.

Regarding policy implementation and governance prime common needs still appear to be capacity building and organising institutional cooperation and data flow. Also, lack of integration across policy areas leaves SQ monitoring schemes largely a sectoral oriented phenomenon (usually focussed agriculture), thus featuring blind spots for non-represented policy areas (usually biodiversity and conservation).

Some countries include socio-economic values and benefits in their ES assessment, e.g., by calculation of the maximum allowable N fertilization levels to soils to protect environmental quality, or by estimation of the maximum monetary compensation to avoid environmental costs associated with alternative land use change scenarios. Such assessments have strong potential for policy implementation.

Indicator selection should be a top-down process where policy-relevant SQIs are selected to inform on predefined policy objectives, rather than a bottom-up process where SQIs are preselected on the basis of localised experience from historical use, cheap costs rather than cost-effectiveness, or -worst of all- scientific lobbyism. Unfortunately, bottom-up approaches cannot be excluded for all established monitoring schemes, and it can be concluded that process guidance on the optimalisation of SQI selection is needed especially regarding national and pan-European applications.

6. National evaluation criteria for soil quality indicators such as references and target values have been implemented scarcely, and primarily concern soil contaminants or nutrient contents in association to allowable fertilisation quota, rather than soil functions relating to ES provision.

Particularly, no reference values exist for soil organic carbon stocks and sequestering (except for 'no decline').

The development of SQI evaluation criteria is therefore crucially urgent, in order to be able to assess EU Green Deal policy objectives by 2030. This also entails contextualisation in terms of soil type, land use and management practices.

7. There is substantial support amongst EJP SOIL MS for harmonised SQ monitoring in Europe.

Although not spontaneously identified as an immediate priority by MS themselves, but when asked, a European harmonisation of a first tier of soil indicators did not raise significant opposition, was considered challenging but desirable, and would receive the support (under conditions) of a majority of MS. This is however not the case for a full standardisation of analytical methods, and in particular reference and target values for SQIs and ES were considered a national matter.

3.6. General recommendations

Soil health definition

The current development in understanding of the Soil Health concept in Europe has been driven forward significantly by the Soil Mission. Importantly, the capacity of soils to deliver ES across an array of seven soil functions has been emphasized. These functions are critical in withstanding major soil threats and therefore are a good start to crystallize the Soil Health concept for policy implementation. However, for a formal definition in legal terms (Soil Health Law, EC in prep. 2023) we recommend that 'soil health' would not be limited to these specified soil functions and associated ES, but would cover a full array of soil-related ES in order to support prevention of potential trade-offs, including cultural ES, and facilitate soil management to support broad bundles of ES.

As sustainability includes aspects of 'people, planet profit', we recognise that social aspects are not explicitly represented in the current conceptualisations of Soil Health in Europe, and indicators for cultural ES are missing. Without engaging in a semantic discussion to evaluate the concepts of ES versus NCP, it is recommended to include some emphasis on cultural dimension in order to promote social equity in sustainable land use.

The definitions in the EJP SOIL Glossary should then be adjusted accordingly.

ES classification

Compared to other international ES typologies, CICES is more universal (i.e., less specific to particular environments and particular beneficiaries) (La Notte and Rhodes 2020) and may therefore be considered as a "default list". CICES 5.1 (Haines-Young and Potschin 2018) defined 83 detailed classes of ES, 29 classes can be identified as soil related and 40 classes as affected by agricultural soil management (Paul *et al.* 2021). A standardisation and harmonisation of ES terminology will facilitate ES assessments in soil research and comparability of results.

Regarding the suitability of the CICES classification for addressing ES in the context of soils and their agricultural management, many constraints have been identified, such as overlaps, gaps, and highly specific or very broad class definitions. SIREN has established differences among Partners in the use of ES terminology and classification that may hamper EU-wide harmonisation and conformity, and clear communication for starters. Close cooperation between the soil research and ES communities could ensure better consideration of soils in future CICES updates and national derivations or specifications from there.

The EJP SOIL vocabulary may also be elaborated in this area. This SIREN report provides recommendations for definitions. By and large, conformity and standardisation of terminology will facilitate scientific review of available knowledge, as the magnitude and rapid expansion of the literature in this field make it necessary to apply automated data mining and text analysis techniques (Minx *et al.* 2017) for which standardized terminologies and indicators are a prerequisite (Hölting *et al.* 2019).

Soil monitoring

Develop a modular system of SQIs, constructed as packages associated to individual soil threats and bundles and trade-offs of ES. Depending on the monitoring objectives and available resources, an optimal composition of modules can be selected. Develop and agree on a basic package for a minimum dataset to harmonise pan-European soil monitoring (see tiered approach, section 5.3.) Synchronise SQ monitoring and ES assessment in time and place. Soil monitoring schemes and natural capital assessments or ecosystem assessments are not tuned to each other, and the discrepancy in sampling times and locations hamper linking and comparison of data.

For SQIs with large potential for inclusion in a minimum dataset in Tier-1, assess the availability of EPFs and pedotransfer functions in scientific literature. As far as these would not be available, it is then an immediate research need to review scientific literature for availability of EPFs for ES assessment for SQIs that otherwise qualify for application in first or second tier SQ monitoring.

Ecosystem assessment

National ecosystem assessments were found to be generally focused on a limited number of ES and because of that can be limited in their potential to assess trade-offs between bundles of ES. Considering the current view on soil health (Giuffré et al. 2021), future ecosystem assessments should be designed to facilitate this aspect of assessment.

NEA reports can be improved to specify what methods are used to extrapolate soil data to quantify ES. Robust ecological production functions are needed to replace the generally common expert judgement approaches to this extend. Assessments should not stop at the level of soil functions, but aggregate to national assessment area levels, and preferably also include socio-economic evaluations to quantify the flow of services towards relevant stakeholders with consequent valuation of costs and benefits.

A methodological drawback is that soil monitoring and ecosystem assessments have not been synchronised in time and space, so that data from different years and places are combined. This should be overcome by better synchronisation and coordination between responsible authorities and practitioners.

Stakeholder participation

The development of national soil monitoring programs will profit from an early involvement of stakeholders, from incorporation of practical knowledge as well as by establishment of acceptance and shared interests indicators and target values for SQ as derived from policy objectives.

Interlinking working groups on soil data

Given the increasing establishment of repositories and working groups compiling soil data, it would be good to aim for harmonisation between these initiatives: ESDAC, FAO Int. Network Soil Biodiversity, SoilBON, Edaphobase, GlobalFungi, SOPHIE, etc.

4. TAKING STOCK

Introduction

The SIREN project made an inventory amongst EJP SOIL Member States on whether and how they apply soil quality monitoring parameters in the main agricultural production systems to assess the provision of ES (also termed Nature's Contributions to People, NCP). This inventory is limited to ES derived from soil functions that can be provided by agricultural soils, including abandoned land. The primary focus was on the *potential* provision, rather than on the actual use, demand, or valuation of ES representing the actual flow of ES or 'benefits' to the farmer and society at large. The draft conceptual framework describing the linkage between SQ and ES that was developed at the start of the project was to be adjusted based on Partners inputs and feedback through this questionnaire.

This questionnaire was circulated to 21 EJP SOIL Partners, representing 20 countries, who had indicated their interest in participating in this stocktake project. Their feedback was used to obtain an overview and synthesis of current indicators and actual reference values of indicators for SQ and ES as implemented in the consortium countries. The results should help to establish commonalities and differences between nations, e.g., with respect to the different pedo-climatic conditions and for the main agricultural production systems across Europe. It was intended to assess how these indicators have been implemented in policy or land management practices across participating nations, and to contribute to EJP SOIL by providing reviewed and synthesised results as input for the updating of the Roadmap and WP3 research program in the ES impact area. For this reason, Partners were invited to identify knowledge gaps and provide suggestions for further development of a research and knowledge agenda in the EJP roadmap. The feedback by each EJP SOIL Partner was relevant to represent all participating nations in the Europe-wide synthesis. On the one hand, this helped evaluating commonalities for potential harmonisation of soil monitoring and ES assessment across Europe. On the other hand, it allowed identifying the unique aspects and needs that differentiate within and between EU regions such as to reflect pedo-climatic conditions or main regional agricultural production systems and cultural differences.

The Lead Partners in the consortium (WR, SLU and INRAE) have composed this questionnaire, and have discussed an earlier draft during the EJP SOIL Annual Science Days with participants representing various consortium Partners, and adapted the draft version since. The questionnaire was distributed to the contact person for each of the 21consortium Partners, and potentially further distributed amongst parties or experts relevant and fit in their country to reply to the questions. A webinar open to consortium Partners was organised to explain the goals and details of this questionnaire and provide for a QandA opportunity.

Methods

The SIREN built on stocktake T2.4.2 (EJP SOIL Deliverable D2.2, Pavlů *et al.* 2021) with an inventory of soil monitoring indicators and datasets at national level among the EJP SOIL Member States. To respond to the SIREN questionnaire, Partners were asked to consider the same soil monitoring programs and databases that had been reported for their country in T2.4.2. The questionnaire provided the list of soil quality indicators as synthesized from the preceding inventory.

The SIREN stocktaking activity had two focal points that were addressed in a single questionnaire:

- EJP SOIL stocktake ES1 focused on soil-related ES. The aim was to take inventory of those ES which are assessed based on soil quality indicators; ES that are not assessed using soil data were not addressed in this survey.
- EJP SOIL stocktake ES2 focused on references and target values for soil quality indicators as applied by MS. As a follow up to the stock take of T2.4.2, this activity was aimed to establish an overview of reference values and evaluation criteria associated to these indicators, and any additional ES indicator following ES1.

The questionnaire consisted of a Word document with questions and two additional Excel workbooks for specification of data regarding the stocktakes ES1 and ES2. The files were organised as a series of separate worksheets addressing a single soil monitoring or ES assessment program at a time, and at relevant governance and spatial scales as well. These soil monitoring programs refer to corresponding databases that were compiled by the MS in the T2.4.2 stocktaking. Regarding these monitoring schemes, the Partners were requested to specify any references and evaluation criteria (target values, threshold values, etc.) for the soil quality indicators used in their country. In the case that in these monitoring schemes indicator data are used for an assessment of soil functions or ES, Partners were requested to specify the procedure in the relevant parts of the questionnaire.
A draft version of the questionnaire was presented and discussed at the EJP SOIL Science Days, 30 March 2021.

Priorities

It was important for the SIREN project that MS feedback could be used in a synthesis to link soil quality indicators to associated ES for the main agricultural systems. Also, references and evaluation criteria for soil indicators were to be associated to specific site conditions and soil management practices.
Feedback was to be synthesized at the national level across EU, hence priority in responding to the questionnaire should be to complete the information at the national level. Secondly, if in addition to national monitoring other programs exist that *differ* in the use of soil indicators, ES, or evaluation criteria, Partners were asked to indicate the rationale behind the differences, as this could help to improve the scientific linkage between soil quality and ES assessment with respect to environmental context.

Analysis of feedback

Feedback by Partners was collated in Excel Files and interpreted, aggregated and synthesized independently by analysts from at least two different Lead Partners, who then discussed differences in their views and agreed on a final interpretation. For transparency of the work, and for future reference, the files have been archived as SIREN Deliverable D1 on the EJP SOIL WP3 SharePoint.

Unanswered questions were filled in by the analysts if reproducible from the context in the Partner's response, else were kept from analyses.

Reading guide

First, a Section Definitions was presented, introducing the key terms used throughout the questionnaire. Partners were asked to respond if these definitions would comply with the use in their country. Alternatives were allowed when better suitable to national or regional standards, if explained.

The questionnaire consisted of four sections (A to D), comprising 65 questions in total, addressing a conceptual framework and actual application and implementation of indicator use in the MS.

Section A introduced the draft for an overarching conceptual framework linking soil quality and ES. This framework was to be further developed as a SIREN project deliverable, and all feedback from this stocktake would be attuned to further development of a final version.

Section B focused on the assessment of soil-related ES based on data measured by soil quality indicators, as it happens in the MS. These indicators can be part of monitoring and research programs at national or lower spatial scales.

Section C assessed evaluation criteria for soil quality indicators and ES assessment that have been implemented in the MS.

Section D focused on policy relevancy and implementation of soil quality-based ES assessment. It was aimed to obtain insights in current obstructions and challenges for implementation of soil monitoring-based ES assessment and perspectives for policy development at EU level.

The questionnaire aimed to take an inventory of soil quality and ES monitoring activities at different spatial scales, and Partners were asked to be as comprehensive as possible, to address the national scale and lower spatial scales as well, if practised.

Below follow the analysis results for the Questionnaire feedback, presented Section by Section.
Original Questionnaire text is in green print.
Contributing persons in the Partner organisations are listed in Appendix 1.

4.1. Questionnaire Definitions

Questionnaire development:	*Isabelle Cousin, Gregory Obiang-Ndong, David Montagne, Jack Faber*
Analysis and reporting:	*Loraine ten Damme, Isabelle Cousin, Jack Faber*

Summary

From initial glossary propositions by the SIREN consortium, the Partners were asked to agree or provide alternative definitions, on vocabulary related to Soil Quality and soil-based Ecosystem Services. In the majority of responses the proposed definitions were acknowledged or left uncriticised; some minor comments have come up, but no radical alternative propositions. Thus, the initial definition of the notion of SQ as presented in the questionnaire was largely accepted by the Partners, albeit more than a quarter of the Partners indicated that only the scientific environment and not the governmental makes use of it, whereas others again use SQ solely related to the utility value of agricultural soils or have named a similar concept as our definition of SQ differently. The SQ concept is somehow rarely used at the governmental level in the development of soil-related policies. To characterise SQ by use of indicators, as defined by SIREN, was recognised by numerous Partners, especially for monitoring purposes. However, even where some partners plead for simple, low-cost and replicable soil indicators, others support the use of complex and integrated indicators. A few partners make use of the term Soil Health instead of Soil Quality, but when specified its definition was close to the SIREN definition for SQ. Soil Health may appeal more to the general public, whereas SQ is traditionally used in the scientific arena.
The concept of Ecosystem Services, as defined according to the TEEB definition as "the direct and indirect contributions of an ecosystem to human well-being", is generally recognised by the Partners. Compared to Soil Quality, the concept is more widely used in governmental organisations and - despite not officially mentioned in legislation – in national environmental strategies. However, it became clear that the distinction between various Ecosystem Services concepts (i.e., capability, capacity, flow and potential supply) is blurred. Perhaps this ambiguity has contributed to a shift of focus away from Ecosystem Services to the broader concept of 'Natural Capital (but not Nature's Contributions to People). For the Partners using 'Ecosystem Services' in agreement with the

proposed definition, CICES is used by a quarter of partners to describe the services related to soil functions, though a distinction between biotic and abiotic Services is hardly made. The distinction between Soil functions and soil-based Ecosystem services still seems to poorly understood, and therefore contributing to erroneous communication, especially because controversial use of the two concepts continues in the scientific literature. Nevertheless, soil functions, especially as defined as bundles of soil processes may be suitable subject of scientific discussion, whereas the soil-based ecosystem services (even if poorly defined) may a be more suitable level of communication at the policy-arena level associating more to the layman's understanding of soil health and closer resembling the ultimate policy objectives that drive the concrete description of "good condition of the environment in the first place.

Introduction

The use of key idioms such as 'soil functions' and soil-related 'ecosystem services' can be ambiguous and confusing. To prevent Babylonian miscommunication and to stimulate "speaking the same language" in this stocktaking activity, the Questionnaire referred to the definitions as already adopted in the EJP SOIL glossary where available (https://projects.au.dk/knowledge-sharing-platform/ejp-soil-glossary/). Definitions for some additional key concepts were also provided with the request to compare to the current implementation in the MS. If the provided definitions would not align with those used in the MS, respondents were free to provide and use their own definitions.

This initial section of the questionnaire established the Partners' definitions of the concepts of soil quality (SQ), soil quality indicators (SQI) and ecosystem services (ES). First, definitions (of SQ, SQI and ES) were proposed and the subsequent questions allowed the Partners to (dis)agree with these definitions (SQ1, SQ4 and ES1) and for them to elaborate when different definitions are used or recommended. The questions SQ1 to SQ6 of the questionnaire related to Soil Quality and the questions ES1 to ES7 related to Ecosystem Services. Considering the Partners' replies, we further refined the SIREN definitions (Section 3.1).

Answers to part A of the Questionnaire have been provided by 21 Partners: Flanders (BE-FL), Wallonia (BE-WA), Switzerland (CH), Czechia (CZ), Denmark (DK), Estonia (EE), Finland (FI), France (FR), Ireland (IE), Italy (IT), Latvia (LV), Lithuania (LT), The Netherlands (NL), Norway (NO), Poland (PL), Portugal (PT), Sweden (SE), Slovakia (SK), Slovenia (SL), Spain (SP), and United Kingdom (UK).

Note: Where our questions were open and broad, the answers by the Partners showed different levels of precision. Moreover, it has been difficult sometimes to disentangle if answers reflected an integrated/national vision – as expected –, or if the respondent rather ventilated a personal view. Anyway, all the narrative answers in this section of the Questionnaire have been interpreted "as is", without judgement on content.

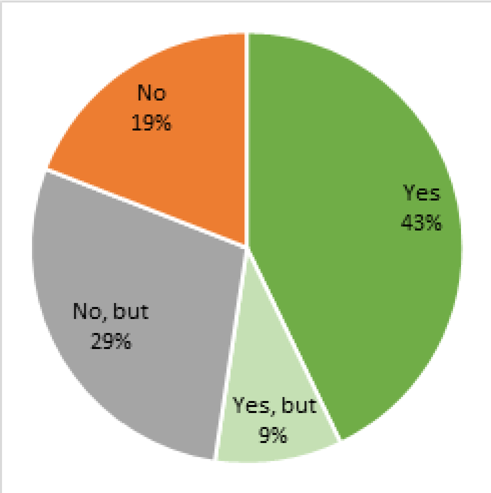
Defining Soil Quality[9]

The proposed definition of Soil Quality (SQ) was "*the (current) 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*" (Doran and Parkin 1994). The adjective "current" was added to the definition of the EJP-Soil Glossary, though in compliance with the Soil Mission Board, to differentiate Soil Quality from Soil Health, which refers to the continued, potential capacity (Soil Mission 2020).

[9] Note that this preliminary definition has been changed following the stocktaking, literature review and stakeholder discussions into the final version as presented in Definitions section 3.1.

Questions SQ1-SQ3

Is the above definition of Soil Quality proposed by SIREN used in your Member State? If a different definition is used, please specify (with references if possible). You are also invited to provide personal or institutional views or recommendations, if different from the EJP SOIL and SIREN version.



About half of the Partners answered that the definition of Soil Quality as proposed is used as such at the governmental level, although it may yet only concern a single national program (as specifically pointed out by NL and PT; 'Yes, but'). Several Partners pointed out that while the concept of Soil Quality is not explicitly used at the governmental level, and therefore not explicitly defined, it is well known and conforms to the proposed definition in the scientific environment (DK, NO, SE; 'No, but'). Norway highlighted that the notion of Soil Quality is increasingly used. Slovakia uses an alternative (a certified soil-ecological unit) in national regulation but noted that the proposed definition of Soil Quality is more suitable. Some of the other Partners do not implicitly refer to the concept of Soil Quality in policy (CH, SK, PL; 'No, but'), but address the utility value of agricultural soils in particular (SK, PL), or have implemented a National Soil Strategy aimed at managing soils so that they can provide relevant soil functions such as soil 'fertility' (but not explicitly 'soil quality' (CH)). A few of the remaining Partners (answering 'No') indicated that the notion of Soil Quality is recognised in policy, but not specifically defined (BE-WA, UK), and that specific legislation on Soil Quality does not exist, but laws exist to act on specific soil threats (SP).

Several respondents (BE-WA, BE-FL, DK, FR, NL, NO, PL and UK) indicated that the notion and concept of Soil Quality have been under development – even for decades (DK). BE-WA noted that a definition of Soil Quality, similar to the definition proposed above, was discussed at governmental level but not adopted. Suggestions were made to further specify the definition of Soil Quality: inclusion of resilience to extremes due to climate change (BE-FL), applicability to land uses other than agricultural (BE-WA), distinction between top- and subsoil (NL), explicit inclusion of economic benefit (PL) and highlighting of the deeply imbedded notion of values (DK).

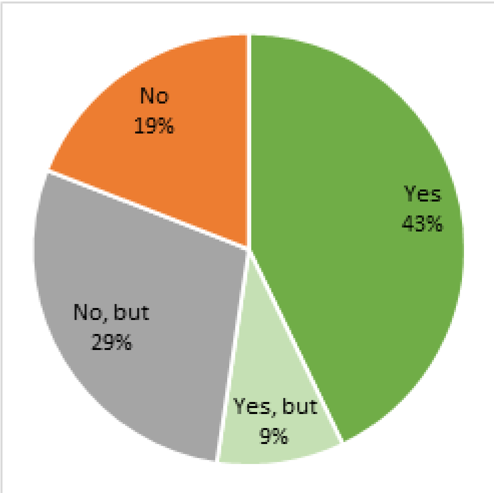
Some Partners raised the notion of Soil Health: NO correctly noted that the Doran and Parkin (1994) definition of Soil Quality is used for Soil Health, while SE defined Soil Health as the "*capacity of soil to provide ecosystem services without negative impacts on the environment*". Some Partners indicated that both terms could be used interchangeably (SE, UK), but did not elaborate on the definition. SE mentioned though a distinction in the users of the specific terms: in the scientific environment Soil Quality is used, while the public uses Soil Health. Other Partners indicated that the term Soil Quality is not specifically used because an explicit definition is lacking, but highly needed (FR, NO). In NO, an expert group developing the National Soil Health Programme chose Soil Health over Soil Quality because the latter was understood as focussed on soil properties and functions considered, whereas the former could address guidelines and mandates of the programme more appropriately.

Soil Quality Indicators

A Soil Quality Indicator (SQI) was defined as "*a parameter, or indicator, or aggregated index, used to characterise the soil state, whatever the objective*". For the purpose of ES assessment, such an indicator may then be evaluated by using Pedotransfer Functions, Ecological Production Functions, crop models, or any sort of model or expert judgement. Note that this definition is wider than the definition defined in the EJP-Soil Glossary, which defines a Soil Quality Indicator as a "*parameter used to quantify and evaluate impacts of agricultural soil practices on soil quality and the environment to draw conclusions for the farming practice or agricultural policy (modified after Piorr, 2003)*".

Questions SQ4-SQ6

Is this definition used in your Member State? [note: the answers are interpreted with focus on the SIREN definition, not the version in EJP-Soil Glossary]. If a different definition is used, please specify (with references if possible); please provide personal or institutional comments or views below, if different from the current national implementation.



The majority of the Partners stated that the definition of Soil Quality Indicators as proposed above is used ('Yes'), including Partners who did not agree with the definition of Soil Quality (PL uses Soil Quality Indicators to assess the utility value of agricultural land). Some Partners mentioned the yet limited use of Soil Quality Indicators (NL) or its restrictiveness to agricultural land (SK), but these particulars fit within the wide definition proposed ('Yes, but').

Other Partners indicated to have no explicit definition of Soil Quality Indicators and/or that no Soil Quality indicators are defined at governmental level ('No, but'), although specific soil properties may be used in assessments (CH, DK, LV, SL, NO; 'No, but'). Sweden indicated that its use is still restricted to the scientific environment ('No, but').

Some contradicting opinions on Soil Quality Indicators were highlighted in the answers: while one Partner (NL) indicated, on a personal note, that parameters may be combined or related to a particular soil condition, as a ratio or more complex index, another Partner (DK) highlighted the risk of doing so: "*Indexing is an effective way of hiding information*".

Some Partners did not acknowledge the use of Soil Quality Indicators (NO) but highlighted the growing consensus that Soil Quality Indicators should be used (BE-FL, BE-WA, UK), for example for monitoring purposes (UK). It is generally considered that Soil Quality Indicators (should) cover a variety of land uses. Partners using Soil Quality Indicators, or comparable indicators, obtain those through measurements and estimations (both pedotransfer functions and expert judgement were mentioned). Some caveats of using Soil Quality Indicators were added, for example due to different constraints resulting from and/or needs for different pedo-climatic specificities (PT, DK) and land use (DK). Few Partners expressed further expectations of Soil Quality Indicators, pleading for indicators to be simple descriptors, with low costs and replicable, and related to data from previous research in case of monitoring purposes.

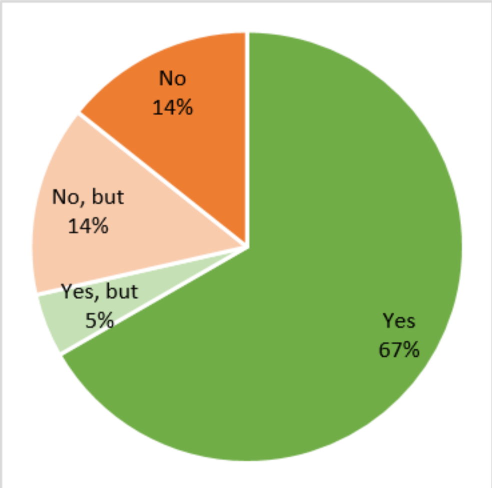
Defining Ecosystem Services

ES were defined, as a baseline, as "*the direct and indirect contributions of an ecosystem to human well-being*", complying with the definition of TEEB Foundations (2010), recognizing the room for adaptation by EU region.

Questions ES1-ES3

Is this definition used in your Member State? If a different definition is used, please specify (with references if possible). Please provide personal or institutional comments or views, if different from the current national implementation.

The great majority of the Partner's responses stated that the definition of Ecosystem Services as proposed above is used in their country, although different words may be used to convey the same meaning. Some Partners stressed, in their own specified definition, the importance of crop quality and quantity (PL) or indicated that the national definition links to biodiversity and the overall landscape, but not directly to soil and its functions (SK). Three Partners (BE-FL, SE and CH; 'No, but') mentioned that they do not officially use a definition of Ecosystem Services, although the term is used mentioned in the nature report on ES (BE-FL), by national Environmental Protection Agency (SE) or implicitly meant when illustrating changes in (and the state of) the environment (CH).



One Partner who acknowledged the use of the definition as stated above highlighting a movement *away* from Ecosystem Services towards Natural Capital (NL; 'Yes'). An interest in Natural Capital instead of Ecosystem Services was also mentioned by other Partners. BE-FL answered that the concept of Natural Capital is explored. The UK has in recent years progressed towards a more encompassing Natural Capital assessment rather than Ecosystem Services ('No'), viewing minerals and non-renewable abiotic subsoil assets as part of the UK's natural capital but not as part of the ecosystem accounts.

While some Partners indicated to move *away* from Ecosystem Services, others highlighted the development of Ecosystem Services, for example when the definition is not yet officially written in legislation but has been indicated in national environmental protection strategies (e.g., SI; 'Yes, but'). These differences in the use of Ecosystem Services versus Natural Capital were not always clarified, and a need was expressed by some Partners to position the concepts relative to each other, as well as to Soil Functions, to further improve (national) definitions of these concepts.

Some suggestions of further development of the definition of Ecosystem Services were to include '(possibly in combination with) human inputs' and to have Ecosystem Services take into account the potential of a (healthy) agricultural soil in both the short- and long-term.

Ecosystem Services of interest

SIREN is focussed on Ecosystem Services that are (or could be) assessed on the basis of soil quality indicator data, and are potentially affected by agricultural management or drivers of change. In SIREN, like in the EJP SOIL program, we are interested in "Agricultural Soil Ecosystem Services", which are defined as "Ecosystem services derived from soil functions that can be provided by agricultural soils", including abandoned land. We do not focus on ecosystem services that are not related to soils and that are not derived from soil data.

Note, that by simplification in the following, we will mention only "Ecosystem Services" (ES), instead of "Agricultural Soil Ecosystem Services".

Potential supply of Ecosystem Services

In SIREN, we are interested only in potential supply of ES, as defined by Weber 2007, Villamagna *et al.* 2013, and Hein *et al.* 2016: "ES potential supply is the ecosystems' ability to generate services irrespective of demand for such services". Services are not always fully harvested; the non-used part

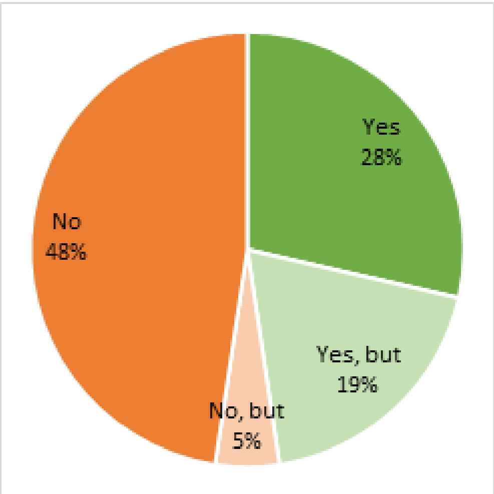
is not quantified as ES benefit, but can be recognised in economic assessments as potential value. In this questionnaire we will use the term ‘ecosystem services’ to mean *potential* ES, which should be distinguished from the actual flow (usage) of ES.
If in addition in your Member State the actual use of these ES is also quantified, and perhaps even the socio-economic costs and benefits, you can indicate that in Section B (Question B16).

Classification of ES
Our default naming and classification of ES follows CICES V5.1 (https://cices.eu/resources/). The classification no longer recognises ‘supporting services’, which are now called ‘intermediary services’ and are largely identical with soil processes that support final services, including ‘provisioning services’, ‘regulating and maintenance services’, and ‘cultural services’ (Haines-Young and Potschin 2018). Final services are discriminated for “biotic” and “abiotic” ES:

- “Biotic ES” are provided by means of biota
- “Abiotic ES” result from chemical or physical soil properties.

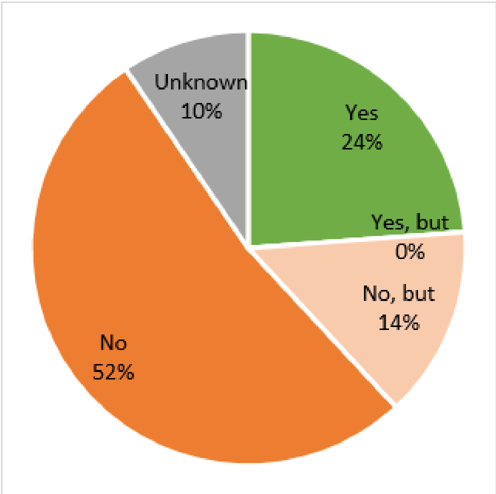
Thus, for example, detoxification of chemicals by the physical sieving and colloidal adsorption by the soil matrix is an abiotic soil quality different from the biotic microbial breakdown and detoxification of such chemicals, with different long-term results and benefits to potentially different stakeholders.

Questions ES4-ES5
Does your country use the CICES V5.1 to describe ES related to soil functioning? If not, what alternative classification is used (e.g. MEA, TEEB, etc.)?



Nearly half of the Partners confirmed using CICES to describe Ecosystem Services related to soil functioning, while a small majority answered they do not. The Partners who do use CICES, either use CICES V5.1 in particular (‘Yes’) or have adopted this or an earlier version to their own use (‘Yes, but’). One Partner stated CICES is used by the Environmental Protection Agency, but not by the
Several of the Partners who said not to use CICES, stated that the Millennium Ecosystem Assessment is used instead, although sometimes only in the scientific environment (DK; ‘No’), or a classification similar to the Millennium Ecosystem Assessment (IT, NO, SK; ‘No’). NO mentioned that an expert panel discussed the use of CICES versus the Millennium Ecosystem Assessment, who concluded that “*CICES is less suitable than MEA for a pedagogic and practical presentation of Norwegian ecosystem services*”. Some Partners stated they use classifications and guidelines developed within their nations (IE, UK; ‘No’).

Question ES6
Do you distinguish between biotic and abiotic ES?



Only a few Partners stated that they, at national level, distinguished between biotic and abiotic Ecosystem Services (CZ, EE, LV, PT, UK; 'Yes'). Three members stated that the distinction is not made at a national level, but elsewhere ('No, but'): at regional level (FR), by the Environmental Protection Agency (SE), or in the scientific environment (SI). Two of the Partners provided no answer to this particular question (CH, LT; 'Unknown'), while they did provide an answer to the other question in this section on definitions. CH provided additional information, mentioning that they do not distinguish between biotic and abiotic Ecosystem Services, as feedback to the draft report.

Soil Functions

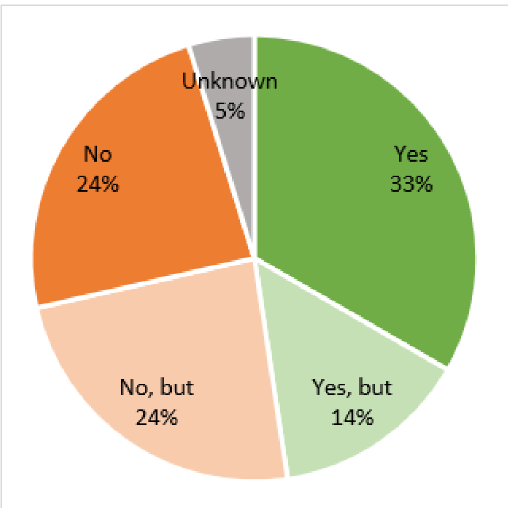
We adopt the definition of Soil Functions in accordance with Glenk *et al.* (2012) and Bünemann *et al.* (2018): "soil functions are (bundles of) soil processes that underpin the delivery of ecosystem services".

Some examples of soil functions are:

- Habitat provision (roots, soil, organisms)
- Element cycling
- Decomposition and humification
- Soil structure maintenance
- Species population dynamics and interactions
- Water cycling (infiltration, retention, percolation)
- Organic matter cycling (humus formation, C sequestration)

Question ES7
Do you distinguish between soil functions and potential supply of ES [or soil-based ES] in your country?

The majority of the Partners do, to some extent, distinguish between Soil Functions and the potential supply of (soil-based) Ecosystem Services. Partners answering 'Yes' (BE-WA, CZ, FR, LT, PL, SK, UK), elaborated on their perspectives on Soil Functions and Ecosystem Services. Generalising, their common view is that Soil Functions relate to (bundles of) natural processes that exist without any reference to humans, whereas Ecosystem Services do not exist without human use, i.e. while Soil Functions is a relatively targeted notion, Ecosystem Services is a broader term, hence, Soil Functions may more frequently be used in research and monitoring than Ecosystem Services. Some Partners indicated that a distinction is made at times (IE, NO, SI; 'Yes, but'). This largely depends on the settings (expert background and purpose, land use). At the same time, one of these Partners stated



that "*In general, the terms are not typically used interchangeably*", but that mainly scientific environment focusses on Soil Functions. The Partners answering 'No, but', stated that both services and functions are used, which in times have different meanings, but could also be used interchangeably (BE-FL, LV). One Partner (CH) mentioned that a distinction is not made, simply because they have no reference to the potential supply of Ecosystem Services. Another Partner (DK) highlighted that the scientific environment differentiates in the terms, but public authorities do not (for DK, this is because authorities do not use either term, but they address specific challenges like nitrogen loss to the environment). Contrastingly, PT pointed out that in scientific literature some overlap between the concepts of Soil Functions and Ecosystem Services exists. Two of the Partners who do not distinguish between the two concepts at a policy level (LV and PT; 'No, but') recognise, from a personal perspective, that Soil Functions and potential supply of Ecosystem Services [soil-based Ecosystem Services] are two different concepts. Some of the Partners who answered 'No', do not distinguish between the two because soil Ecosystem Services are not explicitly considered (SE), or because the terms are used with various and sometimes overlapping meanings (NL, IT). Another Partner (EE) stated that "*Although ecosystem services approach does not differ in essence, the term of soil functions rather than soil-related ecosystem services is used*". One Partner provided no information to this question (FI; 'Unknown').

4.2. Questionnaire Section A: Linking Soil Quality and Ecosystem Services: Conceptual framework

Questionnaire development: *Isabelle Cousin, Gregory Obiang-Ndong, Jack Faber*
Analysis and reporting: *Isabelle Cousin, Loraine ten Damme, Jack Faber*

Summary

National Ecosystem assessments (where existent) do not systematically assess soils, and are two-fold: on the one hand, they are dedicated to improve the knowledge about the functioning of ecosystems (e.g. in the context of the MAES program), and eventually its evaluation under changes, at a national scale; on the other hand, it is linked to the development of decision-tools orientated toward spatial planning or payments for services. For the majority of Partners, soils are theoretically taken into account in these ES assessments, by characterising soil functions or Soil Quality by the use of Soil Quality indicators, the latter being usually evaluated by modelling approaches or by expert judgement.

The SIREN initial framework linking Soil Quality to Ecosystem Services appeared to be close to what half of the Partners have been using, even if more advanced propositions may have been developed regarding demands, values, or governance. Knowledge gaps related to these links between Soil Quality and Ecosystem Services have been highlighted by Partners: these mainly refer to improvements i) in the associated concepts, ii) in the monitoring methods and networks dedicated to the evaluation of Soil Quality, and iii) in the ability of models to take into account changes.

Introduction

The EU Biodiversity Strategy sets specific targets dedicated to ES and required EU Member States to "map and assess the state of ecosystems and their services in their national territory" by 2020. National ecosystem assessments were one approach to comply with these targets. Section A of this questionnaire aims to establish if and *how* soil data have been used in national ecosystem assessments, whether a need is felt amongst the MS for a holistic framework for the assessment of soil-related ES using soil monitoring data, and how the Partners respond to the SIREN framework presented here as a first draft.

The questions A1 to A8 refer to the links between Soil Quality (SQ) and ES Assessments. The questions A9 to A11 refer to the alignment with the SIREN framework.

Answers to this part of the questionnaire have been provided by 20 Partners: BE-FL (Belgium-Flanders), BE-WA (Belgium-Wallonia), CH (Switzerland), CZ (Czechia), DK (Denmark), EE (Estonia), FI (Finland), FR (France), IE (Ireland), IT (Italy), LT (Lithuania), LV (Latvia), NL (The Netherlands), NO (Norway), PL (Poland), PT (Portugal), SK (Slovakia), SL (Slovenia), SP (Spain), UK (United Kingdom).

Linking soil quality and ES assessment

Question A1
What is the main objective of the national Ecosystem Assessment or any other ES assessment in your country?

Answers to this question have been provided by BE-FL, BE-WA, CH, DK, EE, FI, FR, IE, IT, LT, LV, NL, NO, PL, PT, SK, SL, SP, UK

For some SIREN participants this question may not have been easy to answer, either because there is no assessment at the national scale (LV, SL) or because the national assessment does not specifically address soils (SP). Generally, the answers were classified into two broad categories: 1) ES assessments are devoted to improve knowledge, or 2) ES assessments are used in policies or socio-economic activities.

Links with knowledge improvement
Most Partners intend to map and assess the state of the ES in their countries, but the scale at which they intend to do so varies. Some evaluate the state of an ecosystem (CH, PO), others evaluate ES at the national scale (FR, FI, LT) (eventually to contribute to the MAES demand – FR), at the regional scale/local scale (PT, BE), or with the specific objective to identify a prioritised suite of ES (IR) (Figure 10). Some of the Partners would like to provide or evaluate ES reference values (FR, PO), whereas another would like to provide a picture of Soil Quality (SQ) at the national level (NL). Three Partners also intend to analyse the effects of changes by providing a temporal analysis of ES dynamics over time (FR), especially to evaluate the effect of land-use changes (PT, EE). One Partner pointed out using ES assessment as a way of formulating research priorities by the means of an interactive collaborative platform (BE).

Link with policies or socio-economic activities
The Czech Republic reported the wish to protect soils. Several countries pointed out that ES assessments are ways to illustrate the contribution of ecosystems (and biodiversity) to human well-being or social prosperity (NL, BE, LT) (Figure 10). An ES assessment is also seen as a way to support environmental policies in a general way (PO, BE), or specifically on land-use planning at the regional scale (IT) or agroforestry (PT). In the UK, the approach by Natural Capital is used to assist policy-makers in the development of environmental policies. While the NC approach includes non-renewable resources such as coal and gas in the underground, the UK approach otherwise stills seems analogous and in line with the ES framework as proposed. The ES assessment is also seen as a way to develop decision tools at the regional scale (BE, UK), and for territorial/land management planning (LV, FR, SK). Finally, it is seen as a way to develop methods for ES payments, to introduce ecosystem accounting in the general national account system (SK) and to develop new ways to remunerate activities in rural areas (PT), potentially by the development of a method to account for carbon sequestration (BE). PT pointed out the importance of developing the concept of bundles for evaluation of ES payments (question A2).

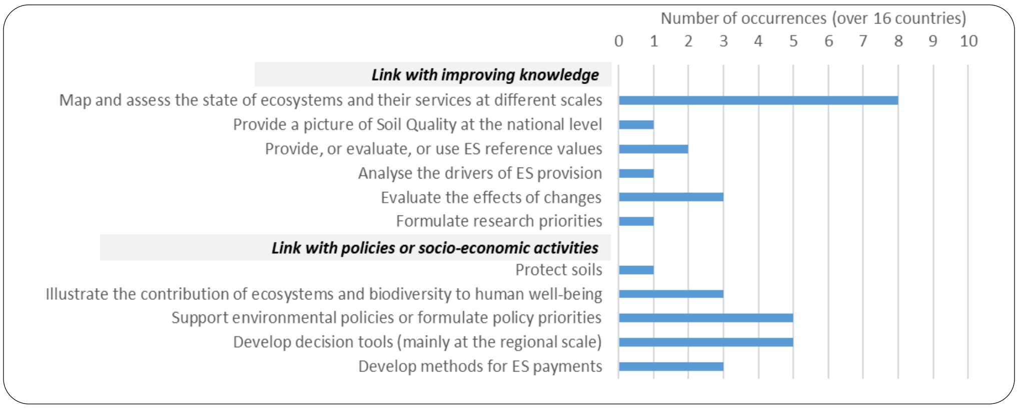
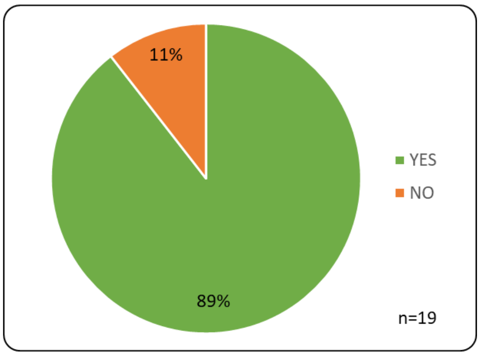


Figure 10. Main objective of the national Ecosystem Assessment or any other ES assessment, as indicated by Partners (Question A1).

Question A2

Are soil-related ES considered in these assessments? (YES/NO). If NO, what is the reason for not considering them?

Answers to this question have been provided by BE-FL, BE-WA, CH, CZ, DK, EE, FI, FR, IE, IT, LV, LT, NL, NO, PL, PT, SK, SL, UK

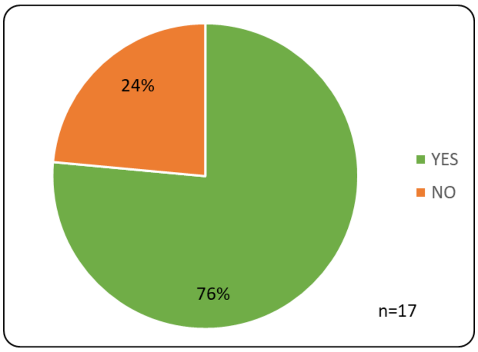


About 90 % of SIREN participants answered 'Yes' (even it may concern only one project, as pointed out by LV). Among the 'No' answers, two Partners mentioned that soil "*[seems to be] unimportant or too complicated to include in ES assessments*" (NO), or that the ES assessments do not consider explicitly ES directly related to soil (CH). Three Partners cited the focus on soil functions instead of soil-based ES: soil functions related to soil C stock changes (NL and IE), water retention (NL), water percolation and infiltration (IE), or specifically on soil erosion. Wallonia notified that "soil" ecosystem assessment is on the agenda.

Question A3

In the national Ecosystem Assessment or any other ES assessment in your country, independent of spatial scale, are any soil quality indicators used to evaluate the potential provision of any soil-related ES?

Answers to this question have been provided by BE-FL, BE-WA, CH, CZ, DK, EE, FR, IE, IT, LV, LT, NL, NO, PL, PT, SK, UK.

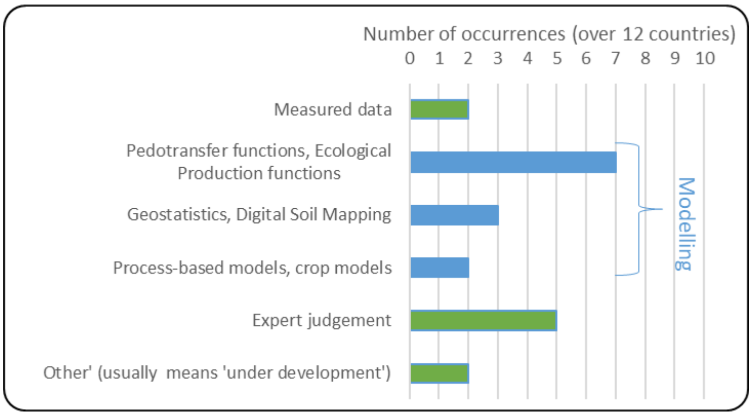


76 % of the Partners answered 'Yes', but NL and LV mentioned that the use of SQ indicators was limited to a single case study. The 'No' answer was given by NO (as mentioned earlier, soils are usually not taken into consideration in ES assessments), by CH and the UK (which do not use the concept of ES in policy assessment), and by SK.

Question A4

How are indicators for soil quality linked to soil functions and soil-related ES, i.e., how do you use soil quality indicators for the evaluation of soil-related ES? Please, describe the methodological procedure below. If no assessment of ES, but of soil functions instead, answer the question mutatis mutandis.

Answers to this question have been provided by BE-FL, BE-WA, CH, CZ, DK, EE, FI, FR, IE, IT, LV, NL, PT, SL, UK. Answers need to be interpreted with care: prelisted answers were provided with the questionnaire, and some countries have given answers selecting from this list, whereas others have not.



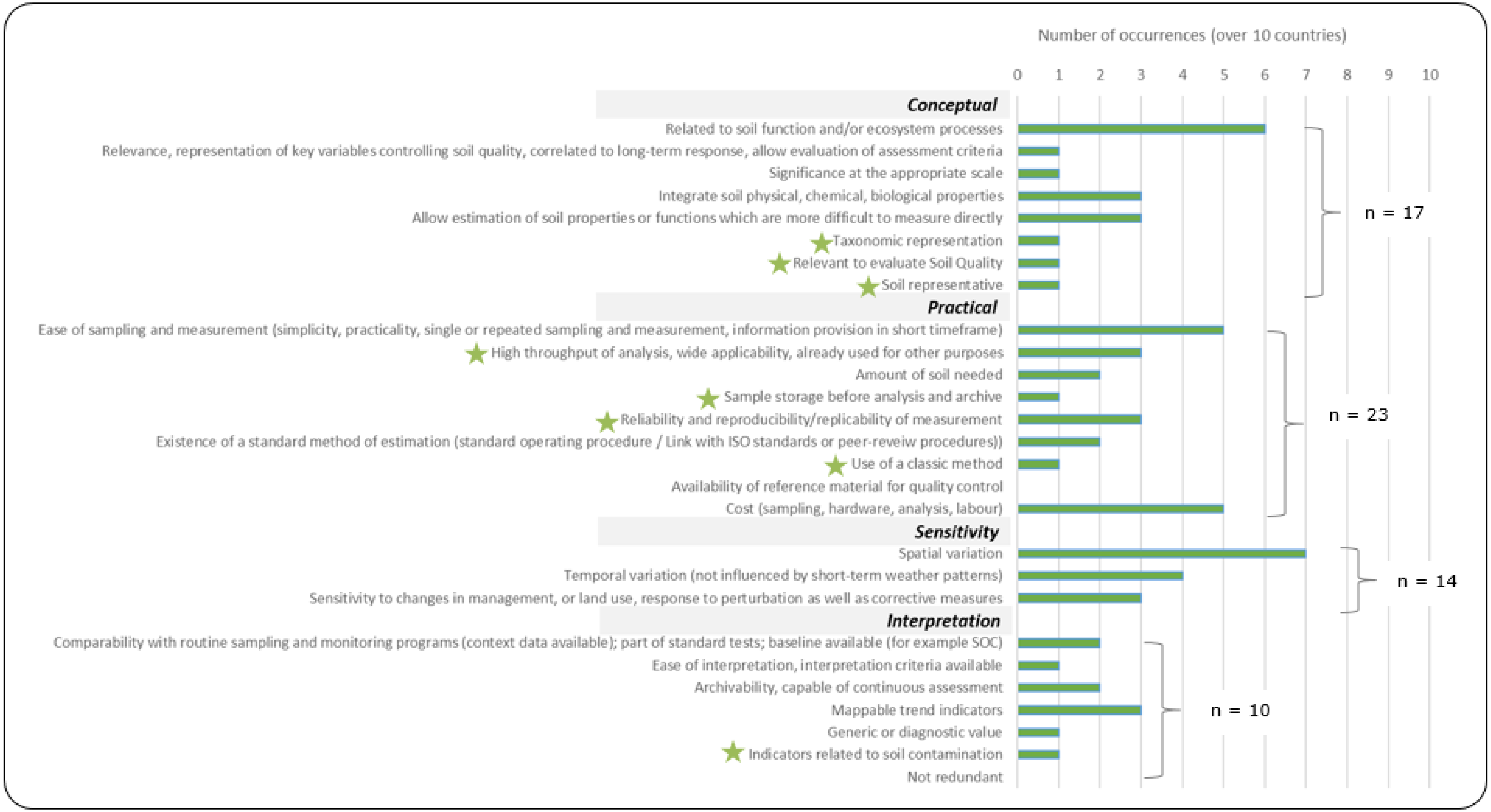
12 Partners answered this question, including two Partners who either have no information on this point or who are still developing methodologies (LV, SV). Most answers dealt with modelling approaches, whatever their complexity, from simple pedotransfer functions to process-based models, including complex crop models. Five Partners mentioned the importance of expert judgement in linking Soil Quality to either Soil Functions or soil ES (CZ, NL, DL, FI, LV). Among specific indicators used, NL mentioned the BISQ, a Soil Biological Indicator (Rutgers *et al.* 2008), BE-FL and EE mentioned an erosion risk indicator based on the RUSLE equation, and IT mentioned using yet other soil biological indicators (BSQ-ar, BSQ-c; Gardi *et al.* 2002) that may link SQ to ES provision and the ARMOSA model to evaluate the impact of crop management practices on soil nitrogen and carbon cycles and groundwater nitrate pollution (Perego *et al.* 2013). For none of all these indicators, the extrapolation from soil data to ES provision was clarified beyond ‘expert judgement’.

Question A5

What requirements for soil quality indicators are considered by your Member State to assess ES?

Answers to this question have been provided by BE-WA, CZ, DK, EE, FR, IE, IT, LV, NL, PL, PT, UK.

This question was an open question, but an initial list was provided to help answering. Most Partners have used the list to answer, except for FR, FI, IT, and PL. BE-FL provided no answer. The UK also specified that SQ indicators are not evaluated “in a consistent or regular manner”. In the figure on the next page, some items have been added or modified by the respondents (marked ★).


Number of occurrences (over 10 countries)
0 1 2 3 4 5 6 7 8 9 10
Conceptual
Related to soil function and/or ecosystem processes
Relevance, representation of key variables controlling soil quality, correlated to long-term response, allow evaluation of assessment criteria
Significance at the appropriate scale
Integrate soil physical, chemical, biological properties
Allow estimation of soil properties or functions which are more difficult to measure directly
Taxonomic representation
Relevant to evaluate Soil Quality
Soil representative
n = 17
Practical
Ease of sampling and measurement (simplicity, practicality, single or repeated sampling and measurement, information provision in short timeframe)
High throughput of analysis, wide applicability, already used for other purposes
Amount of soil needed
Sample storage before analysis and archive
Reliability and reproducibility/replicability of measurement
Existence of a standard method of estimation (standard operating procedure / Link with ISO standards or peer-reveiw procedures))
Use of a classic method
Availability of reference material for quality control
Cost (sampling, hardware, analysis, labour)
n = 23
Sensitivity
Spatial variation
Temporal variation (not influenced by short-term weather patterns)
Sensitivity to changes in management, or land use, response to perturbation as well as corrective measures
n = 14
Interpretation
Comparability with routine sampling and monitoring programs (context data available); part of standard tests; baseline available (for example SOC)
Ease of interpretation, interpretation criteria available
Archivability, capable of continuous assessment
Mappable trend indicators
Generic or diagnostic value
Indicators related to soil contamination
Not redundant
n = 10

The main criteria for SQIs identified were practical elements, related to ease of sampling, wide application (including the use of parameters for other objectives than the indicator purpose for which they have initially been developed), and their reliability /reproducibility as well as replicability; among the 10 answers, all Partners except PL mentioned at least one practical item. Conceptual elements as well as sensitivity were also found to be important: six Partners expressed a need for SQIs to be related either to soil functions or to ES (say, not only to soil state) and seven Partners called for the development of spatially significant SQIs. While unmotivated we think this would facilitate mapping from soil maps and easy linkage to soil types. Other important aspects are costs (mentioned by five Partners), and the ability for SQIs to evolve with time (four Partners). Surprisingly, only three Partners explicitly require SQIs to be sensitive to changes in management or land-use; perhaps this is too obvious a criterion for others to even mention, but we have no clues for this.

Question A6

To what extent in general are these requirements actually fulfilled for the indicators currently in use in your country?

Answers to this question were provided by BE-WA, CZ, DK, EE, FR, IE, LV, NL, PL, PT, SL.

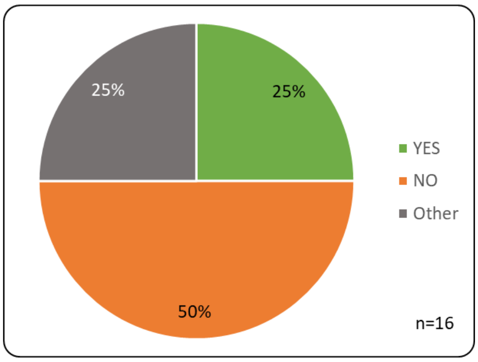
The answers to this question were not easily interpreted in general terms, as they showed large variation and depended on the answers to the preceding question. Below are some specific points raised:

- Elements about accuracy and reliability are not always available.
- Best practices in terms of, e.g., sampling design, data processing and integrity to be developed are project-dependent.
- Some SQIs and/or soil functions indicators may not be available for the calculation of ES due to lack of budget for soil monitoring.
- SQIs are user-dependent: simple indicators may be used by farmers and more complex ones may be used in research projects (they then do not fulfil the same requirements).

Question A7

Does your Member State assess soil-related ES using soil quality indicators that are not part of standardised monitoring (at national or lower scales) in your country? (YES/NO). If YES, please specify and provide references if possible.

Answers to this question were provided by BE-FL, BE-WA, CZ, DK, EE, FI, FR, IE, IT, LT, LV, NL, PL, PT, SL, UK.

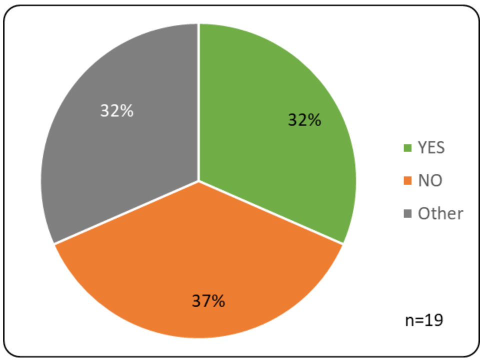


50 % of the respondents mentioned the use of a standardized monitoring system to evaluate SQ (BE-FL, BE-WA, NL, DK, IT, LV, PT, SL, UK). Note that their definition for SQ may differ somewhat, as observed in the introductory part of the Questionnaire. Among them, some also use non-standardized SQIs (probably meaning SQIs not included in their national/regional soil monitoring system) including: Hot Water Carbon, Water Holding Capacity, Aggregate Stability, Visual Soil Assessment, Bulk Density, Penetration resistance, Non-production functions (not described), Microbial denitrifiers, Potential nitrification/denitrification, indicators for soil biodiversity, soil erosion, soil compaction, soil acidification. Quantitative assessment on the use of these indicators is not meaningful, since based on just 5 countries.

For 25 % of the respondents, SQIs are not systematically evaluated by using a standardised monitoring system, and for the other 25 % the use of standardised data depends on the scale of the study (probably using more specific indicators for regionalised studies than for the national level).

Question A8
Instead of extrapolating from soil data to assess potential ES delivery, an alternative approach may be to use existing ES assessment indicators (e.g., yearly crop volumes and market prices, as done in ecosystem accounting, e.g., the MAES project) and further develop cost-benefit criteria for the underlying soil quality. Are such alternative approaches used in your Member State? (YES/NO) If YES, please specify.

Answers to this question were provided by BE-FL, BE-WA, CH, CZ, DK, EE, FI, FR, IE, IT, LT, LV, NL, NO, PL, PT, SK, SL, UK.



A third of the 19 Partners answered 'No', i.e., these Partners do not use alternative approaches to evaluate ES (BE-FL, BE-WA, IE, NO, PT, SK). About another third of the Partners do use alternative approaches, mostly in the form of an economic valuation (CZ and UK) (for example, the evaluation of the Gross Domestic Product for UK), or by other evaluation possibilities (LV, PO, SL). Switzerland mentioned the use of modelling of the evaluation of alternatives like energy demands or plant protection practices. For other Partners, the use of alternative approaches depends on the project/scale: annual yields are used by FR, market prices of crops and commercial fertilizers are taken into account in the evaluation by DK, specific economic evaluations are provided for meadows by EE; FI points out the reference to knowledge from an expert panel.

The SIREN conceptual Framework

The SIREN framework (under development) as it was presented via the Questionnaire is shown in Figure 11. The main elements of the framework are outlined in red, and the focus was on the links between Soil Quality and both Soil Functions and the encompassing ES (red arrow). The idea was to describe how monitoring data (Soil Quality Indicators) can be used to assess the potential provision of associated ES by use of via ecological modelling using simple extrapolation factors or more complex ecological production functions (whatever data is available to do this best).

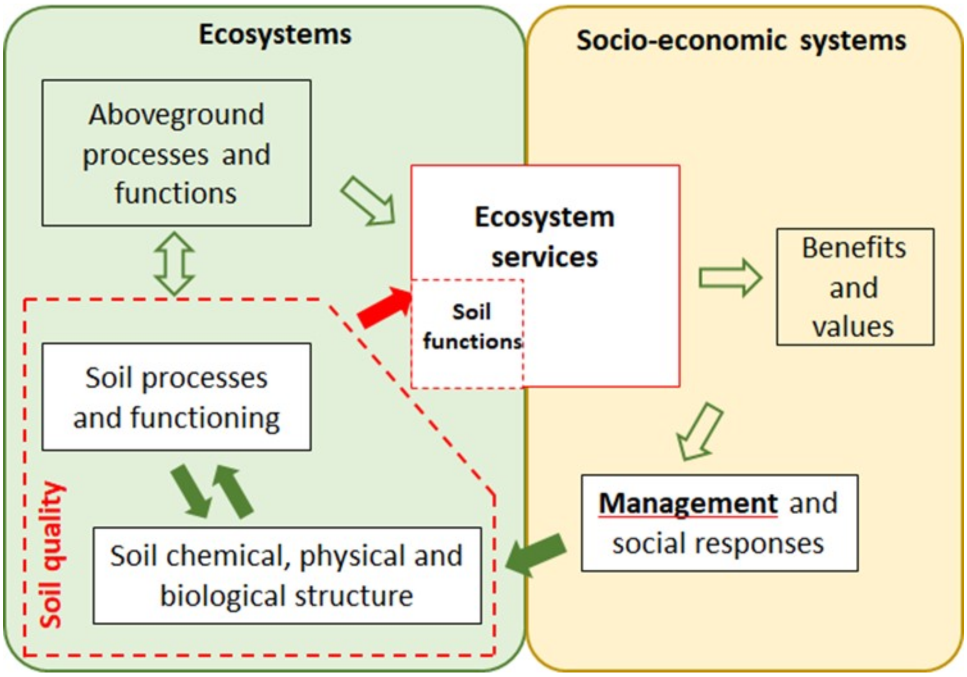
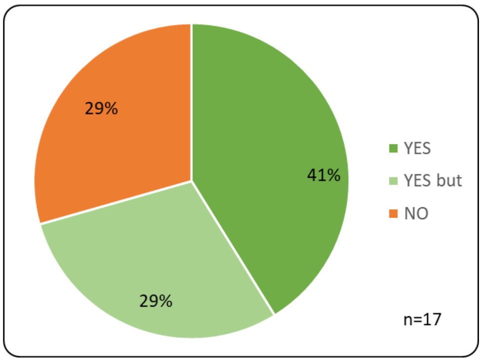


Figure 11. Draft framework linking soil quality to ecosystem services.
Note this is not the final version of the framework, but served to initiate discussion via the Questionnaire.

Question A9
Which parts of this approach are comparable to procedures followed in your Member State? Can you suggest improvements? Please specify.

Answers to this question were provided by BE-FL, BE-WA, CH, CZ, DK, EE, FI, FR, IE, LT, LV, NL, NO, PL, PT, SK, SL, UK.



The answers of the Partners have been used to identify to what extent the framework they are using resembles the draft SIREN framework.
70 % of Partner countries use a fairly similar framework: for BE-FL, EE, FI, IE, NO, PT, SK, the framework is acceptable "as is". For BE-WA, CZ, FR, LV, UK, the framework is closely resembling, but significant modifications have been underlined: BE-WA used a more-developed concept, integrating human demands, values, governance, and values can be used to influence decisions for the ecosystem management; LV uses the cadastral value of the land as part of the ES framework; FR explicitly defined climate and management practices as two drivers citing a framework where the socio-economic system is explicitly split into a social arena and a political arena; UK does not use an ES framework because its policy-based activities now relies on the concept of Natural Capital, but some parts of that framework still match with the SIREN scheme.
For six of the Partners, the approach used in their country is different from SIREN: NL does not assess ES but agriculturally relevant soil functions only, and PL uses a cascade approach from soil properties to benefits and values. Denmark uses a DPSIR approach, and CH currently does not consider soils explicitly in the evaluation of ES (whereas it uses soil indicators to assess soil fertility and soil functioning, which then feeds back into management policies).

Question A10
SIREN has the ambition to identify knowledge gaps related to the links between soil quality and ES. Does your Member State recognise a need for development of modelling linkages between soil quality indicators to assess ES? (YES/NO). If YES, for which indicators-soil functions-soil ES relationships especially? What knowledge gaps are perceived with respect to such ES modelling?

Answers to this question were provided by BE-FL, BE-WA, CH, CZ, DK, EE, FI, FR, IE, IT, LT, LV, NL, NO, PL, PT, SK, SL, UK.

All Partners recognised knowledge gaps and research needs in relation to the links between Soil Quality and ES assessments (Figure 12).
The participants firstly listed ES on which knowledge improvements are needed. We have gathered the answers into a short comprehensive list of services, and we have separated ES and soil threats as focal points for future research. Soil biodiversity was the most cited item on which improvement is considered needed, but its status as soil-based ES or soil property/ characteristic/ process remains unclear.

As far as ES are concerned, CH indicated that "no specific indicator-function-ES relationships are higher in importance than others". Nevertheless, the most important knowledge gap cited by five Partners was carbon sequestration and the role of soil in climate mitigation (Flanders even pointed out to focus on soil resilience to climate change). Among soil threats, emerging chemical threats were identified by FI (neonicotinoids, microplastics, hormonally active agents), as well as changes in climatic conditions. Except for (sub)soil compaction, "classical" soil threats (in the sense of the European Soil Strategy) were no longer identified as requiring further knowledge gaps development.

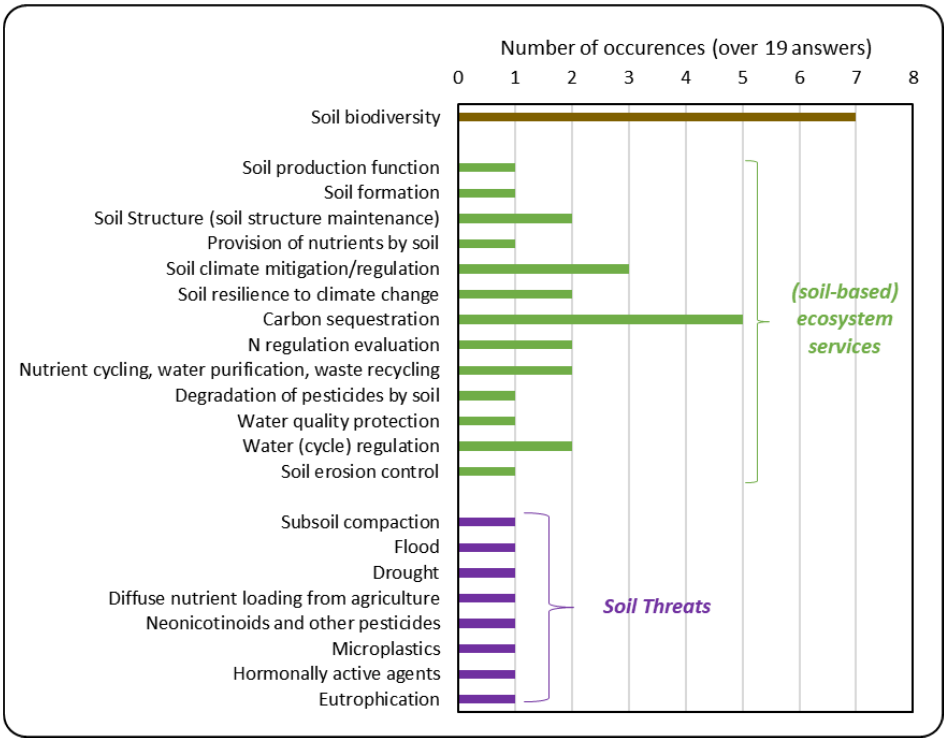


Figure 12. Knowledge gaps and research needs in relation to the links between Soil Quality and ES assessments identified by the Partners (Question A10).

To disentangle the answers by the Partners, we have classified them into three categories: i) soil processes, ii) soil characteristics, and iii) integrated soil indicators (Figure 13A). Soil retention functions as well as soil biological activity and carbon dynamics/carbon content were cited by several of the Partners, but not more than three times. This demonstrates the lack of consensus, which may result from differences between the SIREN Partners in the progress of developing ES assessment.

Partners cited knowledge gaps related to modelling, but not only. The answers were numerous and diverse, and we have categorised them into four classes, dealing with the i) improvements of concepts related to ES assessments (16 occurrences), ii) improvement of soil data monitoring (3 occurrences), iii) improvement of models (19 occurrences) and iv) one item on communication related to raise awareness of ES-related concepts (Figure 13B, Table 3).

Improving conceptual thinking is still an actual need for many Partners: they expressed interest particularly in the definition of the ES concept, how to deal with multiple services and with multiple stakeholders, the development of indicators (for example: indicators related to soil biodiversity; integrated indicators) and harmonisation between Partners, even a proposal for normalization was raised. Measurements of soil data dedicated to ES assessment also were considered to need improvement: three Partners underlined the need for soil data at the local scale, and satellite information was cited as a tool which could be developed. Numerous answers were linked to model development or usage: improvement of models themselves is required to deal with temporal/spatial variation, upscaling facilities, and evaluation of multiple services. Practical considerations on the use of models, i.e., their validity domain and how they can be parameterised, or validated in a specific context, are also of interest. Several Partners expect specific outputs from the models, for example an ability to evaluate nutrient losses and SQ decline from drought, or to include economic valuation (carbon sequestration accounting methods, for example). Finally, several Partners expressed a need for operational decision tools, for example for use in spatial planning.

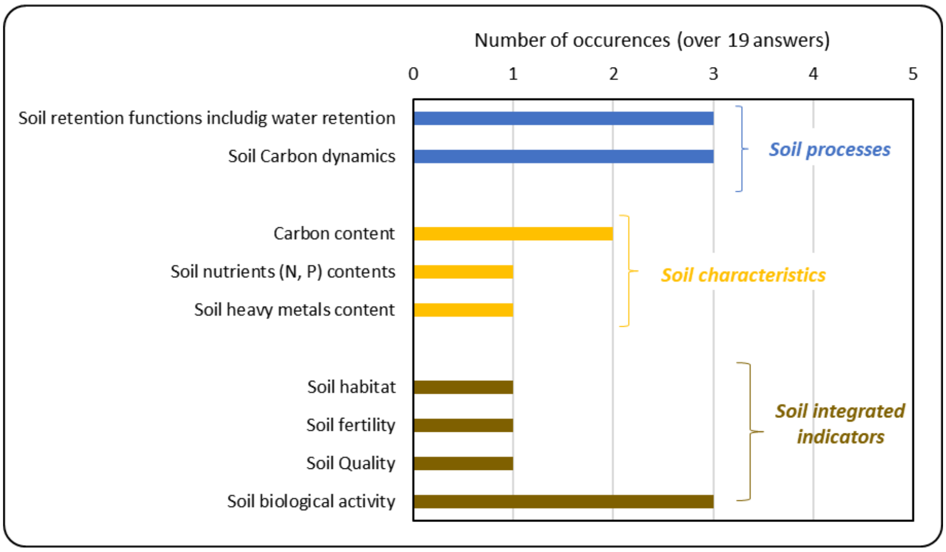


Fig. 13 A

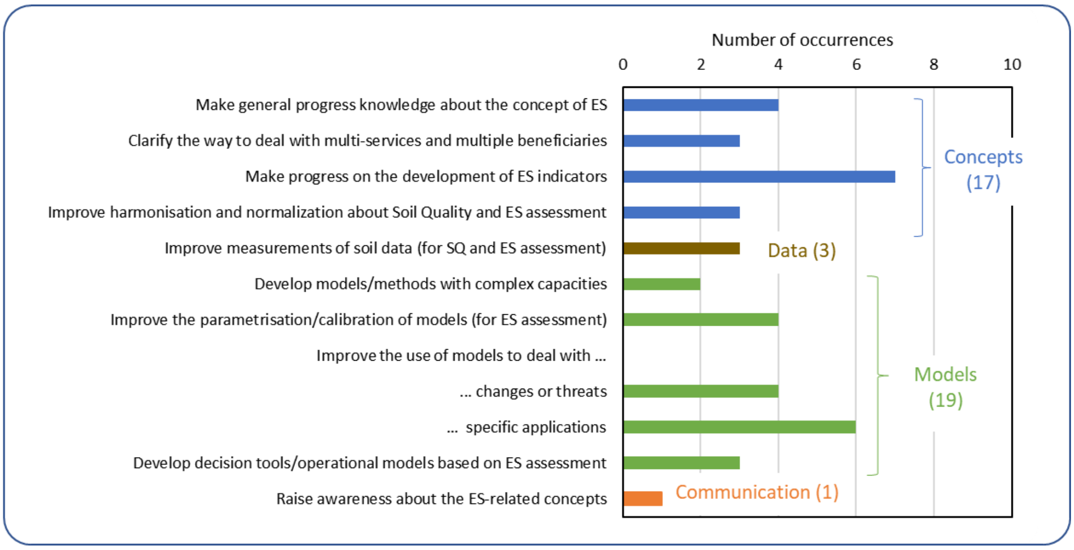


Fig. 13B

Figure 13. Knowledge gaps and research needs (Question A10) categorised according to two angles: (1) into "soil processes", "soil characteristics", "integrated soil indicators" (panel A), and (2) into "concepts", "data", "models", "communication" (panel B). For the latter, the complete answers are presented in Table 3.

To be comparable to other Sections of the Questionnaire, and to interpret knowledge gaps in a unified way all along this document, they have also been classified in a third, harmonized way (Figure 14). Definitely, this part A of the questionnaire has helped to identify knowledge gaps for research, and especially the development of indicators and establishing relationships between Soil Quality and Ecosystem Services can be implemented. To a lesser extent, needs for harmonization, implementation, and communication toward stakeholders were mentioned by the Partners (Table 3).

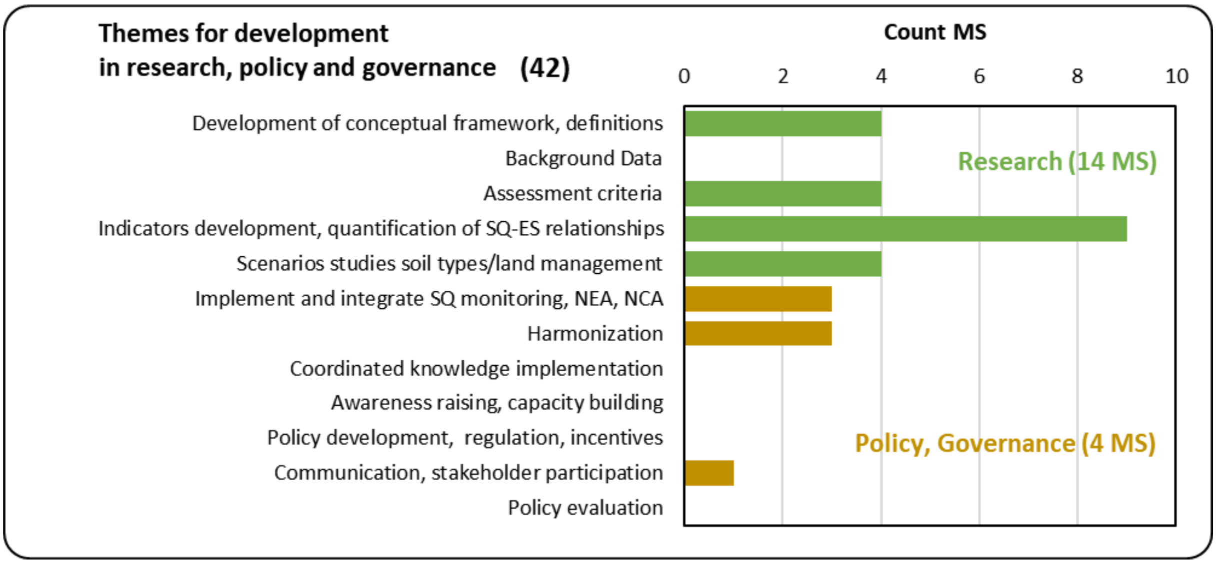


Figure 14. Knowledge gaps indicated by the Member States in relation to Framework development, clustered in 12 standardised categories used for all Questionnaire sections for comparison; five categories related to research (green bars) and seven related to policy and governance (brown bars). A total of 42 different themes were raised (Table 3). NEA, National Ecosystem Assessment; NCA, Natural Capital Assessment.

Question A11

Do you have any other comment related to this section of the questionnaire?

Two Partners provided complementary comments. These have been included under question A10.

Table 3. Compilation of knowledge gaps identified by Partners regarding the link between Soil Quality and ES assessment

Make general progress knowledge about the concept of ES

- Develop conceptual work to elaborate on/clarify some ES definition
- Precise the ways from indicators to functions
- Develop a common system to assess the value of ES
- Improve the methods to deal with both biotic/abiotic processes
- Make a review of quantitative links between SQ and ES

Clarify the way to deal with multi-services and multiple beneficiaries

- Improve the evaluation of bundles/multiservices
- Elaborate on the multifunctionality of ecosystem and the diversity of beneficiaries
- Elaborate on the management of an ecosystem with multiple benefits to multiple stakeholders

Make progress on the development of ES indicators

- Improve the definition of some ES indicators
- Improve the knowledge of relationships between SQI and soil functioning
- Develop SQI related to soil biodiversity
- Develop SQI related to provisioning ES
- Develop SQI related to regulating ES
- Develop integrated indicators
- Develop a Soil Health Index

Improve harmonization and normalization about Soil Quality and ES assessment

- Normalize the use of models for the evaluation of soil quality
- Develop intercomparable methods
- Define a harmonized list of soil supporting services

Improve measurements of soil data (for SQ and ES assessment)

- Some data are missing at the local/regional scale
- Use easily obtainable soil spatial information (including satellite)
- Improve the measurement of adequate soil parameters

Develop models/methods with complex capacities

- To account for temporal variations
- To take into account time to evaluate services with long-time processes (e.g. nutrients dynamics, water purification)
- To Deal with parameterisation of models due to lacking data (management farming info.)
- To integrate the uncertainties in the evaluation of ES
- To upscale local data to landscape scales
- To evaluate some "integrated" services like climate regulation, water regulation

Improve the parametrisation/calibration of models (for ES assessment)

- Define ranges and threshold which are context-specific
- Deal with uncertainties in measured data
- Deal with variation of ES under different pedo-climatic conditions, soil management

Improve the use of models to deal with …

- ... changes or threats
    - Improve the quantification of benefits and losses from non-productive functions
    - Evaluate the management impacts on indicators for delivery of multiple services
    - Develop methods to assess future trends
    - Propose ways to influence C sequestration to mitigate CC though soil management
- … specific applications
    - Quantify benefits and losses due to floods and droughts to society
    - Develop efforts to reduce nutrients loads
    - Improve links between soil-C measurement to C-sequestration
    - Evaluate models which allows the evaluation of threats to soil quality
    - Develop Carbon sequestration accounting methods

Develop decision tools/operational models based on ES assessment

- Apply concept of ES into planning processes and strategies

Raise awareness about the ES-related concepts

- Raise awareness of ES concept to vulnerable groups
- Make ES concept more concrete

4.3. Questionnaire Section B: Ecosystem Services assessment based on Soil Quality Monitoring

Questionnaire development: *Marjoleine Hanegraaf, Jack Faber, Maria Viketoft, David Montagne*
Analysis and reporting: *Katharina Meurer, Jack Faber*

Summary

The usage of soil quality indicator (SQI) monitoring data for assessment of ecosystem services (ES) or soil functions is not widely distributed across the EJP SOIL member states. More precisely, less than half (nine) of the Partner countries that responded to the questionnaire indicated that they include some kind of SQI in ES assessment. Out of those nine, only four countries have reference values or other evaluation criteria for specific indicators established. These reference values are not necessarily uniform at national scale, but grouped based on soil types (sand, clay, loam, peat), farming systems (arable land, permanent grassland, vineyard, orchard, agroforest) and climatic conditions, relief and slope of land.
Sustainable agriculture was mentioned as one of the main objectives for the ES assessment by five Partners, followed by environmental monitoring (mentioned by three3), adaptation to climate change (one country) and soil protection (one country). Most Partners are aware of the CICES classification and use it during the ES assessment. However, this use depends on the monitoring program and some programs may use other ways of classification (e.g., reference values).

Monitoring programs are generally directed by higher instances, i.e., the national or regional government. However, most databases used for ES assessment are fed by research projects or programs. Those programs mostly operate on spatial scales smaller than the national scale (e.g., regional, sub regional, local scale), depending on, for example, geological conditions, agroclimatic regions or soil types.

One of the most important soil quality indicators mentioned by the Partners is SOC (C concentration, SOC stocks, organic matter quality, and organic matter decrease) – however, the translation of observations of SOC is very different across countries. The approaches cover different types of models (crop models, response functions, pedotransfer functions), as well as assessment factors, expert judgements and meta-analyses. For the models and assessment factors, some of the MS provided a reference to the methods and equations used for translating SOC information into ES. Yet, none of the Partners specified how the *expert judgement* had been derived and how it is used in practice.
Besides the potential supply of soil-supported services (e.g., C cycling/storage and sequestration), Partners indicated that they also assess the socio-economic values and benefits related to this use. This includes, for example, estimates of the commercially optimal (= allowable) N fertilization or even an estimation of the maximum monetary compensation to avoid environmental costs associated with different land use change scenarios using ES. In the latter case, the results of this project feed into CAP policy by proposing adequate payments for ES as implemented in the country.

Based on the answer given by the Partners, the awareness of soil quality indicators in national or regional ES assessments is still rather minor. Even though some countries have programs that are about to start or have recently finished, the majority of the MS does not plan any ES assessment in the near future.

Introduction

SIREN aimed to establish to what extent EJP SOIL associated MS are currently assessing ES based on their soil quality monitoring, and whether countries encounter knowledge gaps in the process. From this information it is to establish which ES are considered most important by MS, as well as feasible steps for future development.

The T2.4.2 stocktake of indicators from national monitoring programs, soil data collection and other programs that produce soil information databases (reported in EJP SOIL deliverable D2.2) serves as a starting point for this questionnaire section. For the sake of brevity, hereafter these are called 'monitoring schemes'. These monitoring schemes were to be reviewed to evaluate their use in the assessment of soil-related ES.
The questions in this section B have been clustered in the following topics:

1. Identification of monitoring schemes
2. ES assessment
3. ES evaluation criteria
4. Supplementary questions

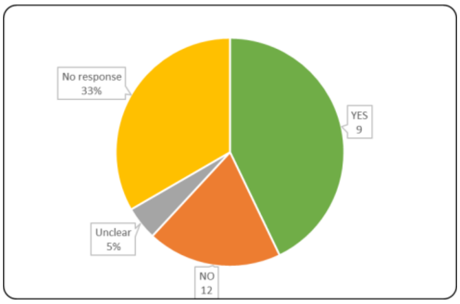
Answers to part B of the Questionnaire have been provided by 21 Partners: Flanders (BE-FL), Wallonia (BE-WA), Switzerland (CH), Czechia (CZ), Denmark (DK), Estonia (EE), Finland (FI), France (FR), Ireland (IE), Italy (IT), Latvia (LV), Lithuania (LT), The Netherlands (NL), Norway (NO), Poland (PL), Portugal (PT), Sweden (SE), Slovakia (SK), Slovenia (SL), Spain (SP), and United Kingdom (UK).

Not all questions have been answered by all Partners. However, some blanks for "Yes/No" questions could be filled based on the answers given in the subsequent questions.

Identification of monitoring schemes

Question B1

Are soil quality indicator monitoring data used in your Member State to assess ecosystem services or soil functions, either in a national assessment or otherwise?



Of the 21 Partners that responded to the questionnaire, only nine indicated that soil quality indicator (SQI) monitoring data was used to assess ES (ES) or soil functions (FR, NL, BE-FL, CZ, EE, FI, IE, IT, and PT). Four Partners responded that in their country no use is made of soil quality indicators (LV, SE, CH, UK), and eight did either not give a response at all (BE-WA, DK, LT, NO, PL, SL, SP), or the response was unclear (SK). Only those Partners that responded 'Yes' were included in the further analysis of monitoring schemes and ecosystem assessment (Questions B2 to B13).

Question B2

Which other monitoring or research schemes in your Member State provide soil data for ES assessment?

Several Partners (CZ, FR, BE-FL, EE, FI, IE, IT, PT, and NL) pointed out that that they have other research schemes that provide soil data for ES assessment, e.g., different kinds of soil maps (erosion, sealing, landslides) or databases from sporadic research projects or surveys instead of national monitoring programs. A particular focus on agrochemical parameters has been reported by CK, EE, FI, and PT. In NL monitoring schemes are being developed by agribusinesses for payments schemes for farmers on the basis of "key performance indicators" (Van Doorn *et al.* 2021).

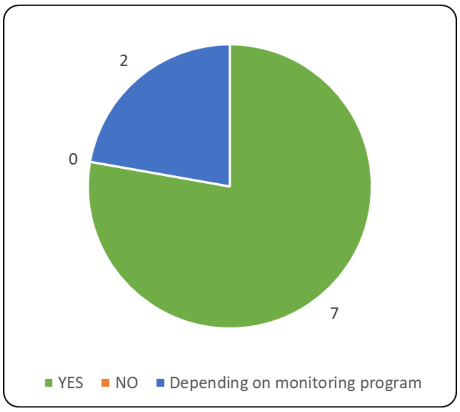
Question B3

For monitoring or research schemes listed under B2, please explain the reasons for differences compared to the national approach. We are particularly interested to understand if such differences are driven by geographical and/or ecological context.

In most cases, the differences between the programs listed under B2 to the national approach were driven by a geographical or geological context. In Flanders, for example, the *landslides map* only covers a particular part of Flanders due to the geological conditions. Similarly, the *Heavy Soil Programme* in Ireland only considers the western half of the country where heavy soils are found, despite being considered a national programme. The *SQUARE* programme covers the main agroclimatic regions and soil types clustered by drainage classes. The programme *SIS* represents the main soil types of which some are geographically concentrated. For example, calcareous soils are only found in the west of Ireland. In addition to that, *ACP* focuses on only six catchments that are however representative of the main agroclimatic regions and farming systems. In the Finnish *Soil Fertility Test*, the derived data is owned by the farmers and usually not available for research purposes. However, if required, the data is aggregated at municipality level. The samples collected during this test are collected by the farms themselves at different times (every fifth year) and do, consequently, not follow a very strict methodological rigor. France highlighted, that they use coarser maps and databases (currently a 1:1.000.000 database) to avoid using data from different origins. However, for local evaluations, the data has to be more precise. In Estonia, full spatial coverage of detailed soil data is provided by large-scale soil map at scale 1:10.000 with the main element of extrapolating modelling across agricultural landscape (Kmoch *et al.* 2021) In contrast to the other MS, different programs have different targets in The Netherlands and monitoring programs for payment schemes involving soil and ES data are actually primarily focusing on milk production, C sequestration, subsoil or on recommendations for individual farmers. In addition, a national monitoring programme on subsoils exists.

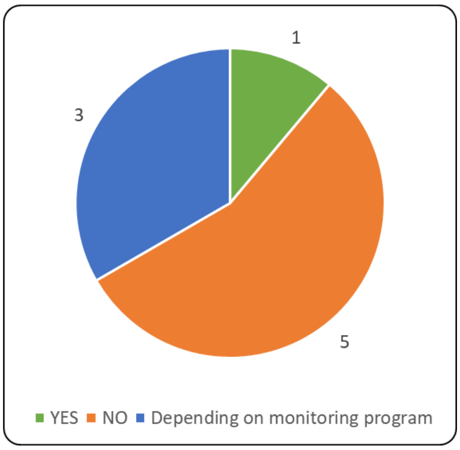
Question B5

In the monitoring program, do you differentiate the assessment of soil-supported services with respect to land cover and/or land use?



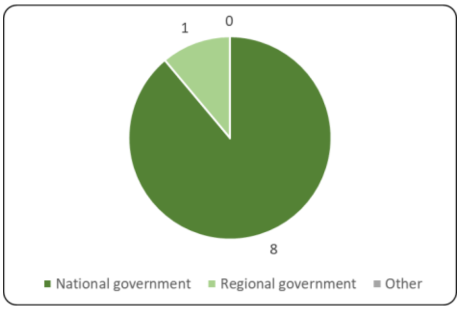
For the national or regional scale (e.g., regional scale for Flanders and Wallonia), the majority of Partners (7) indicated that they indeed distinguish between different land cover and/or land use in their monitoring. Some countries have, however, more than one monitoring programs running simultaneously (e.g., BE-FL, FI, IE and PT) and not all programs make the above-mentioned distinction. Flanders and Ireland mentioned that one of their programs does differentiate between land use or land cover (‘Depending on monitoring program’).

Question B6
In the program, do you differentiate the assessment of soil-supported services regarding soil management schemes?



Only one Partner (EE) answered that they differentiate their ES assessment regarding soil management schemes, while five Partners answered 'No' to this question (NL, BE-FL, CZ, FI, and IT). France, Ireland and Portugal indicated that this is treated differently in different monitoring programs.

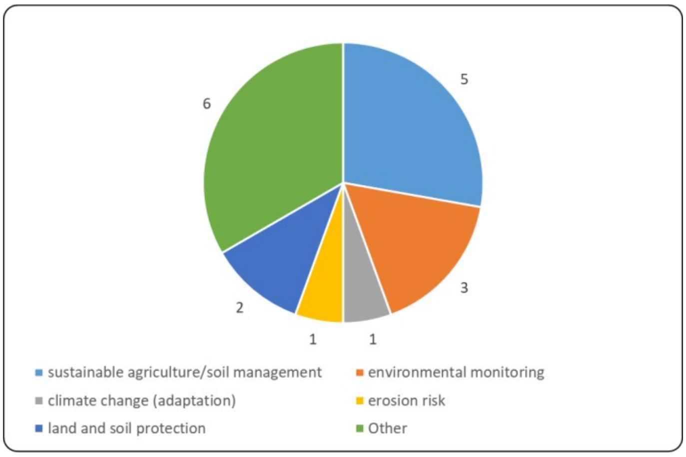
Question B7
What is the responsible authority of the research program?



The majority of the Partners (8 out of 9) indicated that the monitoring programs were guided by the national government (e.g., the Ministry of Agriculture). In the case of Flanders, the regional authorities are the highest instance. In most cases, the research/monitoring programs are additionally supervised by research institutions.

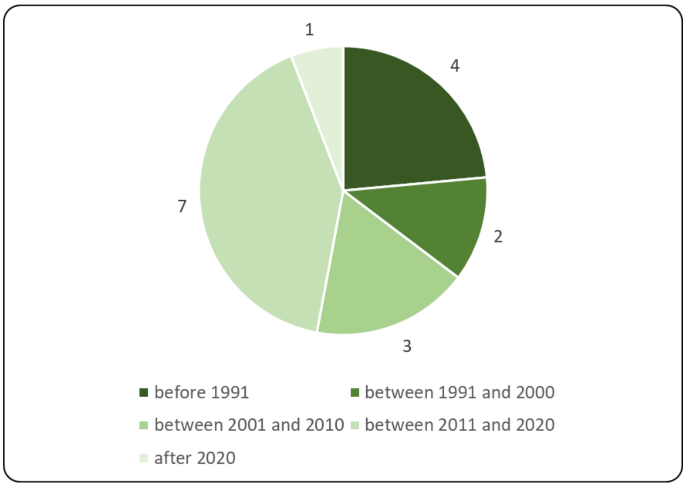
Question B8
What are the ES assessment objectives of the monitoring schemes (e.g., sustainable agriculture, environmental monitoring, climate change)?

Sustainable agriculture was mentioned as one of the main objectives for the ES assessment by 5 Partners (FR, NL, BE-FL, FI, and IE), followed by environmental monitoring which was mentioned by 3 Partners (BE-FL, CZ, and FI). Climate adaptation was brought only by Flanders, while only the Czech Republic indicated that land and soil protection was one of their assessment objectives.



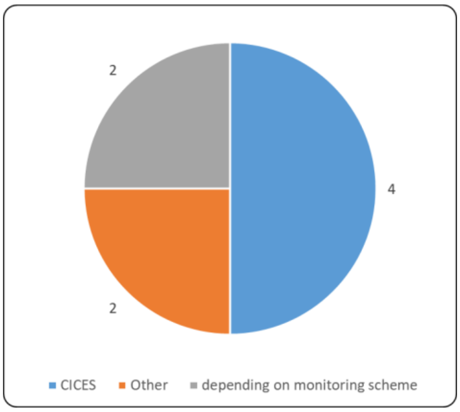
Apart from the above-mentioned objectives, some countries specified additional objectives (summarized under "Others"): In France, specific objectives are given by the MAE - however, these have not been specified by the respondent. The risk of landslides is the objective of the respective monitoring program in Flanders. Estonia indicated that they have objectives related to both policy and management, but these were not further specified. The *Valse* program in Finland aims at monitoring the chemical quality of agricultural soil for agricultural production and C storage purposes. Similar to this, the Irish *ACP* program evaluated measures in the Nitrogen Action program and has a strong focus on nutrient losses. In Italy, the main objective of ES assessment is the impact of land consumption.

Question B9
In what year did the program start?



The Czech Republic, Estonia and Finland reported that their programs have been initiated before 1991, where Finland specified the *Soil Fertility Test* and *Valse* programs. Two programs have been running for between 21 and 30 years (initiated between 1991 and 2000; Ireland (*NSDB*), Portugal (*Contamination*)). Portugal further stated that the databases behind *Proposolo* and *Infosolo* derived from just one measurement date, i.e., they are not considered monitoring programs. Flanders started two monitoring programs between 2001 and 2010 (*erosion* and *landslides*) and the *ACP* program was started in Ireland in 2008. The majority of the monitoring programs have, however, been initiated between 2011 and 2020 (Flanders (*soil sealing*), Ireland (*HeavySoils, SIS, SQUARE, Tellus*), Italy, Portugal (*Montado*). Please note that the assessment of soil-related ES has not necessarily been initiated at the start of the respective monitoring program. The Czech Republic highlighted for example that even though their program has been running for more than 50 years, the assessment of soil-related ES has only started in 2019. Neither France not the Netherlands answered this question.

Question B10
Does your Member State use the CICES v5.1 classification for ES?



The CICES v5.1 or some other version of CICES is used in Flanders (CICES-BE), the Czech Republic, Estonia, and Portugal. France and Italy indicated that they use different classification systems. In France, for example, a specified list of ES exists and one of their programs on C stocks follows a list given by the French National ESA for agriculture. In 2 countries, the CICES classification is being used in only some of the programs: while CICES is used in the Finish *Valse* program, the Soil Fertility Test uses reference values for the evaluation of the soil status. Similar to that, the Irish *NSDB* program uses the CICES classification, while a soil function approach after Schulte *et al.* (2014) is used in the *SQUARE* program. No answer to this question was provided by the Netherlands.

Ecosystem services assessment

Question B12

In the monitoring programs, how are soil indicators related to soil organic carbon (C concentration, C stocks, OM quality and SOM decrease) used to assess ES?

The Partners were asked to select from a dropdown menu the mode how in their country soil indicators are translated into ES: crop models, pedotransfer functions, assessment factors, other models, expert judgement or other means. Here, we only focus on soil indicators related to SOC, i.e., C concentrations, C stocks, organic matter quality and SOM decrease. Also, the results are presented for the national scale, if not denoted otherwise.

In France primarily crop models are used in order to estimate water and nutrient related services, such as (blue) water provision, water quality regulation, groundwater (only at regional scale), nitrogen provision to crop, biomass production and climate regulation.

Models other than crop models are used by several countries at the national (EE, IE), regional (BE-FL) and subregional (FR) scale. In Estonia a linear regression is used in order to determine total N (N_{tot}) in mineral soils as a function of soil C content ($N_{tot} = 0.047 \cdot (SOC \cdot 1.724) + 0.0366$; Roostalu 2008). This is then further being used to estimate the yield of Reed Canary Grass (Kukk *et al.* 2011). Pedotransfer functions (PTFs) are used to predict certain soil properties using data from field-based soil surveys, such as texture information (Kmoch *et al.* 2021). On the national scale, countries such as Flanders and Estonia use those kinds of functions to assess services such as regulations of soil quality or natural hazards based on soil C concentrations. In the case of Estonia, PTFs are used to assess the spatial distribution of C concentrations from information on soil texture and soil type (Kmoch *et al.* 2021). The derived distribution of C concentrations is then used to derive the soil bulk density (BD) as $BD = 1/(0.03476 \cdot (SOC \cdot 1.724) + 0.6098)$ (Adams 1973, Kauer *et al.* 2019). This allows further derivation of eco-hydrological parameters at a high resolution.

Assessment factors are used by the Czech Republic and Ireland (national and regional scale), as well as Italy (regional scale). For the latter, the focus is on assessment of the soil organisms habitat and climate regulation in the region Emilia Romagna in Northern Italy. More specifically, the potential to preserve soil biodiversity (BIO) is determined by the soil organic C (OC), the bulk density (BD), as well as an index for assessing the biological quality of soil based on the number of micro arthropod groups adapted to the soil habitat (QBS_{ar}; Parisi *et al.* 2005): $BIO = (\log(OC \cdot 1.742) - BD) + QBS_{ar}$ (Calzolari *et al.* 2016). In addition to that, OC is used to calculate the soil cation exchange capacity (CEC), which is one of the indicators used to assess the natural attenuation capacity of soils (filtering and buffering): $CEC = 6.332 + 0.404 \cdot \text{clay content} + 1.690 \cdot OC$. The climate regulation effect of soils is assessed by changes in C stocks – more specifically, a national average of C stock change is determined following the IPCC guidelines for GHG inventory.

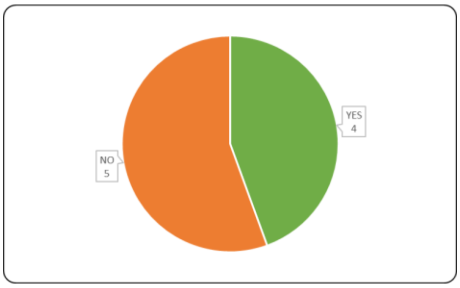
Expert judgement has been mentioned by some Partners as a mode to assess biomass provision (EE and PT), regulation of soil quality (EE), and erosion regulation, mediation of wastes, and groundwater (PT). However, none of the Partners specified how the judgement had been derived or how it is being used in practice.

The assessment mode used in Finland did not fit the suggested categories (other means). Using data from the monitoring programs and meta-analysis, in Finland changes in C stocks are assessed and, consequently, the regulation of C stocks; impacts of soil organic matter content are also considered when determining N and P fertilization limits for fields receiving environmental subsidies (e.g., Heikkinen *et al.* 2013, 2020; Valkama *et al.* 2013; Peltovuori 1999).

Ecosystem services evaluation criteria

Question B13

In the monitoring schemes, have ES reference values or other evaluation criteria been established? If yes, are these evaluation criteria specific for the monitoring schemes, or uniform at the national level?

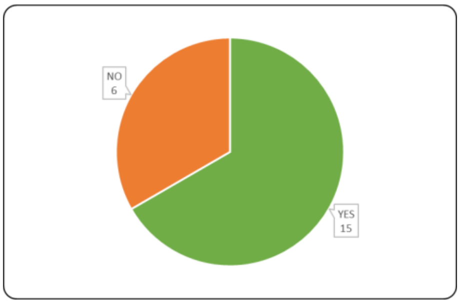


France, the Czech Republic, Ireland and Italy stated that they have ES reference values or evaluation criteria.
In the case of France, these values are applied at the national level and are solely limited to cropland (pasture data is not included). In the Czech Republic, reference values and criteria are used in different contexts, such as (i) soil texture class (sand, clay, loam, peat) and physical-chemical properties, (ii) farming system (e.g., arable land, permanent grassland, vineyard, orchard, agroforest), (iii) climatic conditions, relief, slope of land.

Supplementary questions

Question B15

When recording soil quality indicators, do you also record site conditions such as management history, current practices, climate conditions?



Please note that this and the following questions include <u>all Partners</u> that provided an answer and independent of their answer to question B1, which was if they use soil quality indicators in their monitoring programs for ES assessment. More than two thirds of the Partners answered that they record different types of site conditions when recording soil quality indicators (FR, NL, BE-FL, BE-WA, CZ, DK, EE, FI, IE, IT, LT, NO, PL, PT, SK, and CH). Mostly recorded is the current land use and vegetation, as well as the geomorphology/geology/terrain and the climatic condition/weather (Figure 15). The (historic) land management is only assessed by less than half of the countries mentioned above. Texture as a soil property was mentioned by 4 Partners, but from the T2.4.2 stocktake it was clear that all countries include this parameter. Only Flanders mentioned that meta information, such as georeferencing, sampling date and farm type is collected.

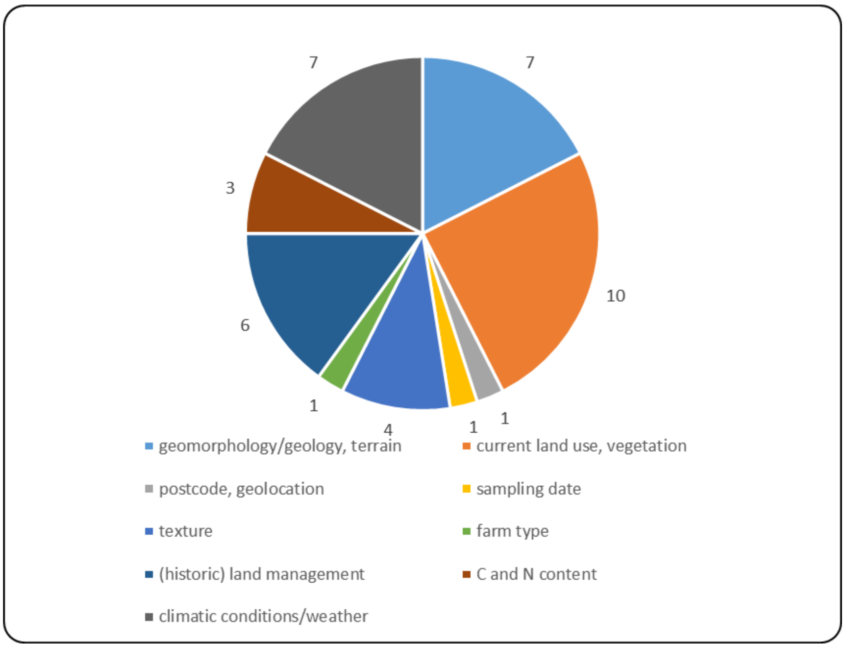
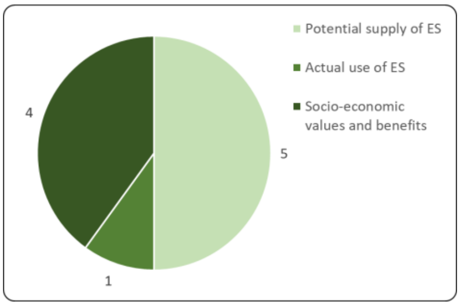


Figure 15. Additional information recorded in national monitoring, and the number of countries.

Question B16.1

Regarding the level of ES assessment at the national (or next highest) level, do you assess: (i) the potential supply of soil-supported services, (ii) the actual use of soil-supported service, (iii) the socio-economic values and benefits associated to this use?



Five Partners (FR, FI, IE, IT, SK) reported that they assess the potential supply of soil-supported services at the national level. In France, this targets mainly changes in management practices, in particular irrigation or fertilization. In Ireland, several projects focused on soil-supported services related to carbon cycling/storage and sequestration. Similar to that, Italy mentions that 11 soil-supported ES are evaluated at the national level on the basis of potential supply. Soil-ES have been monitored in France over the last 30 years, with socio-economic value assessed for biomass production, water provision to crops, blue water provision and N provision to crops. In addition to that, four countries (DK, FR, IT, PT) assess the socio-economic values and benefits. In Denmark, the model providing estimates of the commercially optimal (i.e. allowable) N fertilization includes market prices for crop products as well as fertilizers. In Portugal, the project *Ecopol* involves an economic assessment in the multifunctional cork and holm oak agroforestry system (*Montado*) in Southern Portugal. Within the project, an economic evaluation exercise of three ES (soil protection, nutrient retention, and carbon sequestration) is performed, by estimating the maximum monetary compensation to avoid the environmental costs associated with two land use change scenarios. The results of this project feed into CAP policy by proposing adequate payments for ES provided by the *Montado*.

Question B16.2

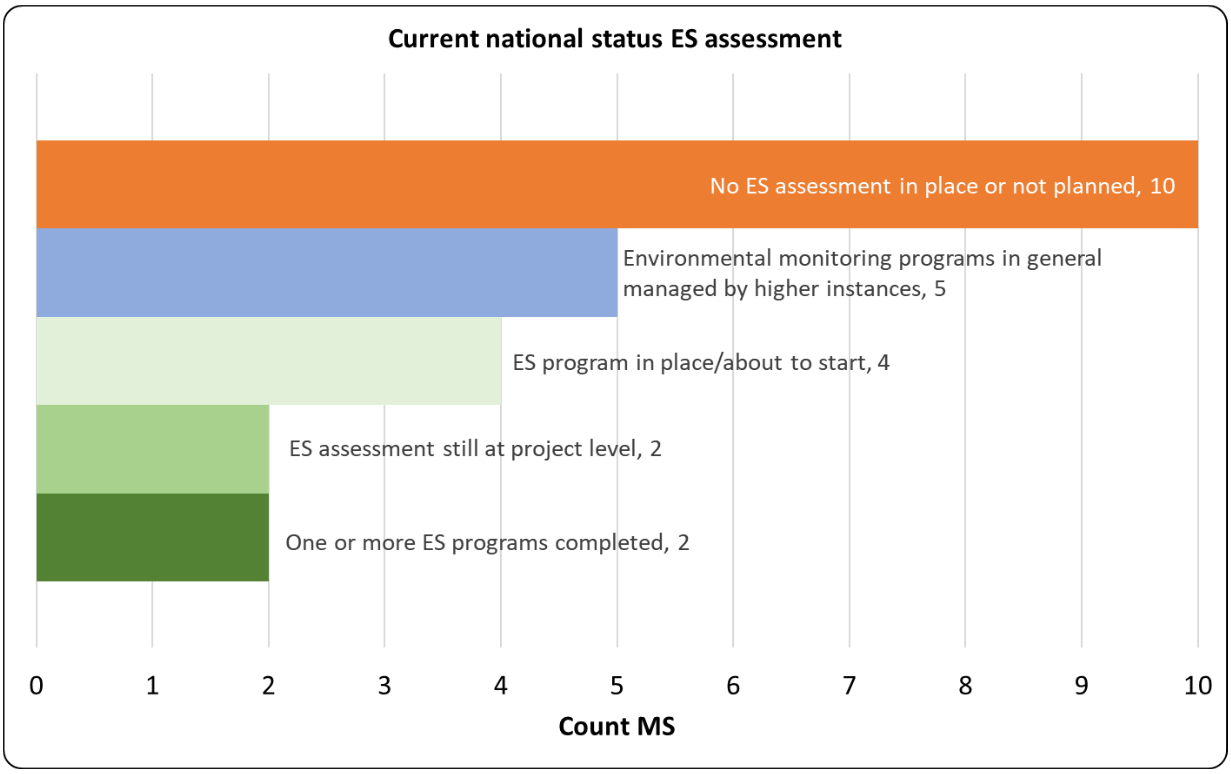
If different for regional scaled ES assessments, specify below.

On the regional scale, only France, Wallonia, and Italy reported the assessment of at least one of the above-mentioned services. In France, the potential supply of soil-supported services is assessed within the *Hauts-de-France* ES assessment, whereas the actual supply is being assessed for the regions Brittany and the *Saclay* plateau. In Italy, the potential supply is being assessed within several projects and databases, e.g., LOSIS, Soil Water Monitoring Network and the *Portale del Suolo*.

Question B17

What is the current national status of ES assessment in your Member state, considering, e.g., national competence and actions necessary for improvement?

Three countries have programs supporting ES assessment in place or are about to start a new program (BE-FL, EE, FI). LV will develop a monitoring system for agricultural soils not including ES, but that is carried out by several projects. Most countries have no national ES assessment implemented (BE-WA, IE, IT, NO, PL, PT, SL, CH, UK, and SE). The reasons for missing ES assessments given by the individual Partners range from the need for a clear definition of the target ES and ES in general (e.g., NO, PT), the current development of methodological approaches using research projects (SL), the need for improved knowledge integration and decision support tools (IE, IT) to limited (financial) resources (BE-FL, SE). As for the latter, in Flanders, the focus of national monitoring programs is on other soil processes, e.g., soil degradation. In Sweden, funding from environmental agencies only covers sampling and data compilation and only a small part of the data actually goes to analysis. Consequently, ES assessment happens primarily at the project level, but is not part of environmental monitoring programs that are initiated by higher instances (BE-WA, CZ, DK, LV, SL, and SE).



Nevertheless, in FR and EE programs including ES assessment have been completed, e.g., the *MAES* program (FR), and *ESMERALDA* and *ELME* (EE). Nationwide assessment and mapping of baseline levels of ES in EE in the *ELME* project has not been explicitly focused on providing and analysing soil-related ES.

Question B18

Regarding the assessment of ES on the basis of soil monitoring data, what is considered the biggest immediate knowledge gap hindering further development or policy implementation; what would be the most urgent research priority for your country?

The knowledge gaps raised by the Partners could be assigned to 10 of the 12 categories identified in SIREN (Figure 16). Those categories were split into rather research-related ones and those focused towards Governmental actions.

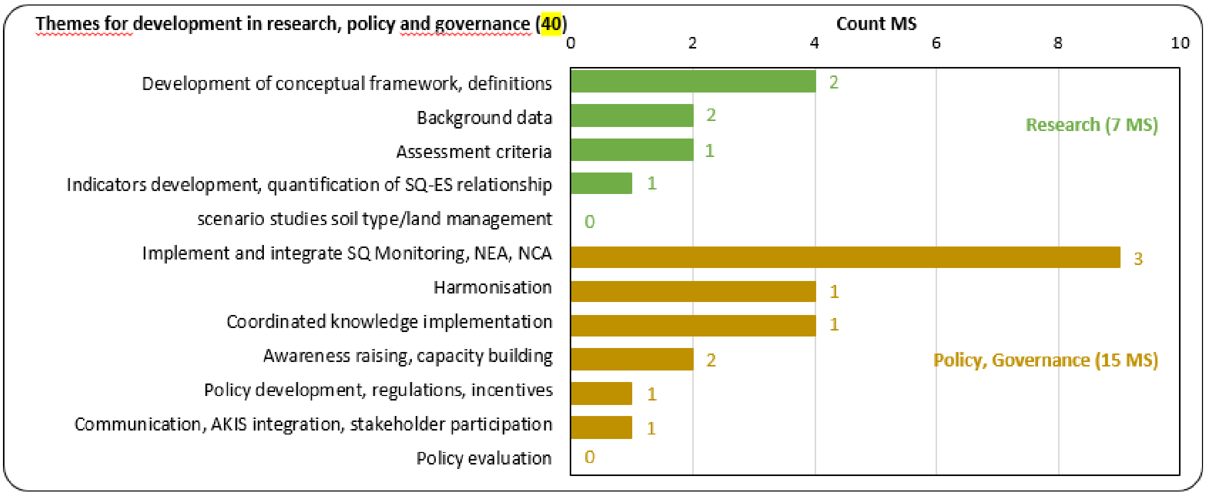


Figure 16. A total of 40 knowledge gaps in relation to ES assessment based on soil quality monitoring, clustered in 12 categories; five categories related to research (green bars) and seven related to policy and governance (brown bars). The numerals at the top of bars indicate the total number of different topics that were specified. Research needs were specified by Partners for 7 countries, and for 15 policy development needs were indicated. NEA, National Ecosystem Assessment; NCA, Natural Capital Assessment.

The basis of successful policy implementation certainly lies on the research side and starts with a better understanding of key processes determining SQIs and ES (BE-FL, DK, and FI). In addition to that, NO pointed out that there are still too many knowledge gaps regarding the practical implementation of improved management practices. These gaps fall within the category of *Development of a conceptual framework and definitions*. In terms of availability of *background data*, Ireland raised the issue of a missing baseline that allows indication of the direction of change of a specific parameter, while FI indicated that the subsoil is being omitted in current investigations. Further, the translation of soil data into an ES context is not clearly defined in some countries, e.g., PL and CH (*Assessment criteria*). FI mentioned that different data types should be connected for the development of spatially more accurate soil maps, which would be an asset for both research and policy implementation.

For the knowledge gaps related to governance, it became clear that there needs to be a guidance on how to achieve the implementation of ES into politics – however, it also became clear that countries are still at very different parts of this way. The very first step might be *Awareness raising and capacity building*, meaning that there should be an economic assessment of non-productive functions in soils and the landscape (CZ) and a better demonstration of the cost-benefit ratio of, e.g., C measurements (BE-WA). ES should in general be better acknowledged in an agricultural context (NO), which improves *stakeholder participation and communication*. The most important point raised by the Partners is the *implementation of SQ monitoring and ES assessment*. So far, there is no monitoring program for soils linked to ES, or existing programs have been stopped in IE, LV, LT, SK, and CH. SL suggested to supplement national soil monitoring programs with missing SQI and influential site information in order to assess ES. However, SK and DK pointed out that the financial resources for that kind of monitoring are missing. In a next step, data should be harmonized within but also across countries. However, methodologies and protocols for that are not yet available and/or not uniform (BE-FL, EE, PL, and PT). This next step is then the judgement of which soil functions are more important in certain regions (*coordinated knowledge implementation*) (PL, PT, SL, and CH). In a final step, the monitored SQI and ES have to be translated into policy and management practices (*policy development, regulations, incentives*), which has specifically been pointed out by BE-FL.

4.4. Questionnaire Section C: Evaluation criteria; Referencing and targeting soil quality

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Analysis and reporting: *Chantal Hendriks, Ava Gillikin, Katharina Meurer, Jack Faber*

Summary

This section provides an overview on evaluation criteria implemented by countries to referencing and targeting soil quality. Most countries have references or reference values for soil quality indicators implemented in the national soil monitoring program. Responsible authorities are mostly (associated to) government or ministries. Although policy objectives for defining references or reference values are quite similar between countries, the values are very different and the methods used to develop these values are also diverse. Reference values differ among countries, but also among soil quality indicators. C-concentration and P availability are soil quality indicators for which most frequently reference values were defined. However, a quantitative analysis on the values implemented in the different countries is not possible because the use of these values depends on, for example, soil depth or soil type. Threshold and trigger values are implemented by much fewer countries. Especially soil quality indicators related to physical soil parameters, such as soil water content, physical degradation, and salinization, as well as biological parameters are underexposed. Partners mentioned the need for reference values on biological parameters. The lack in defining reference values is related to the lack in regulations for agricultural soils, data/monitoring, relation between national criteria and ecological approaches, large variation over space and time, and priority from (national) governments. Not knowing at which level of detail or accuracy spatial and temporal soil quality monitoring needs to take place, and the lack in a robust, harmonized approach on monitoring soil quality indicators hamper the development of monitoring schemes and evaluation criteria for soil quality indicators. To bridge knowledge gaps from soil quality indicators to soil functions/ES there is suggested to develop an approach that evaluates soil quality and the delivery of ES in a more holistic way (e.g., *Natural Capital Programme*), or a tool (e.g., *Biofunctool* of France) that classifies soil functions. This all will start with consistent monitoring programs for agricultural land or pedo-climatic zones

Introduction

In Section B Partners have been asked about monitoring schemes for soil quality and ES in the country. Section C focused on the implementation and further development of references and other evaluation criteria in relation to the indicators used in soil monitoring and quality assessment.

One of the main objectives for the SIREN project is to record actual use by Member States of reference, threshold and target values for soil quality indicators, in the different pedo-climatic conditions and for the main agricultural production systems. Section C is dedicated to this purpose.

Evaluation criteria in soil quality monitoring schemes may involve different concepts and levels of evaluation. Regarding the soil quality indicators used, reference values may be used to reflect some "good status", threshold or trigger values may be used to set a limit to acceptability for discrepancy from such a good status, and target values may be specifically aimed at a particular land use or policy objective, or may be 'integrated' across different (policy) objectives, e.g., reflecting soil, water and climate policy goals at the same time.
A higher level of evaluation may be distinguished, when references and targets are composed of a set of indicators, while each indicator may still feature a specific reference value. Thus monitoring data can be integrated into indices for integrated soil quality assessment as well as for integrated policies around soils.
But the definitions and use of these concepts are likely to differ among MS, and Section C aims to gain overview of these differences and commonalities, and the need for further development and implementation.

Both references and thresholds for soil quality indicators are required for their operational use to inform management and policy. Indicators ideally are clearly and unilaterally related and responsive to specific management or external drivers of change, (facilitating an evaluation of the direction and degree of change), and reference values may reflect the context of local soil and climate conditions, specific agricultural systems, and adopted management practices. The questions aim to identify commonalities and differences among MS in setting evaluation criteria for soil quality indicators, and to clarify any differentiation in evaluation criteria with respect to specific policy objectives that may trigger soil monitoring – if applicable.

MS responses to this questionnaire will help to identify commonalities in the use of particular indicators and references, and these may offer potential for "easy" harmonisation across the EU. However, it is also acknowledged that Member States may cherish particular, perhaps unique aspects in their monitoring and evaluation of soil quality, hence SIREN will also help to identify such 'specific needs'.
Thus, the questions in this section address:

- technical aspects regarding implementation of indicator evaluation criteria in monitoring schemes in your Member State
- needs and challenges for further development of evaluation criteria in Member States and EU.

As a follow-up to the preceding EJP SOIL stocktake of T2.4.2 (Pavlů *et al.* 2021), which had come to an inventory of indicators used, SIREN established an overview of reference values and evaluation criteria associated to these indicators. The indicators listed are soil parameters, representing a range of physical, chemical and biological aspects of soil structure and processes.

Answers to part C of the Questionnaire have been provided by 21 Partners: Flanders (BE-FL), Wallonia (BE-WA), Switzerland (CH), Czechia (CZ), Denmark (DK), Estonia (EE), Finland (FI), France (FR), Ireland (IE), Italy (IT), Latvia (LV), Lithuania (LT), The Netherlands (NL), Norway (NO), Poland (PL), Portugal (PT), Sweden (SE), Slovakia (SK), Slovenia (SL), Spain (SP), and United Kingdom (UK).

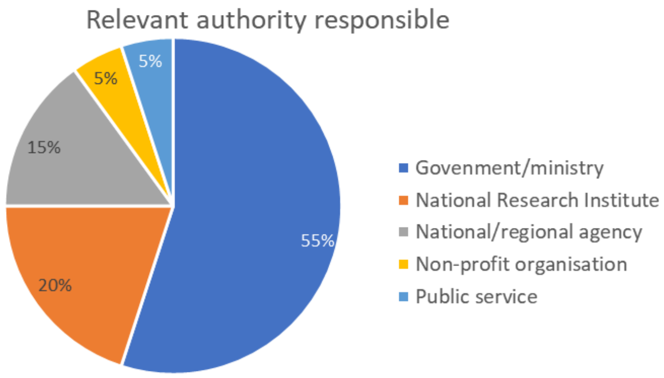
Partners did not answer every question. Blanks can have different meanings (e.g., respondent did not know the answer, forgot to answer, or had no information available to answer the question). Despite such blanks, much useful information was gained on the diversity among countries on evaluation criteria, and referencing and targeting of soil quality.

Technical aspects

Question C1.

Have references and reference values or other evaluation criteria for soil quality indicators been implemented in the national (or next highest governance level) soil monitoring program? If yes, then specify the relevant authority responsible for the assessment.

Soil quality indicators (SQI) references and reference values have been implemented by 81% of the MS (based on 21 countries that responded to the questionnaire). Predominantly, the government or ministries are responsible authorities for implementation (55%) .



Question C1.1.

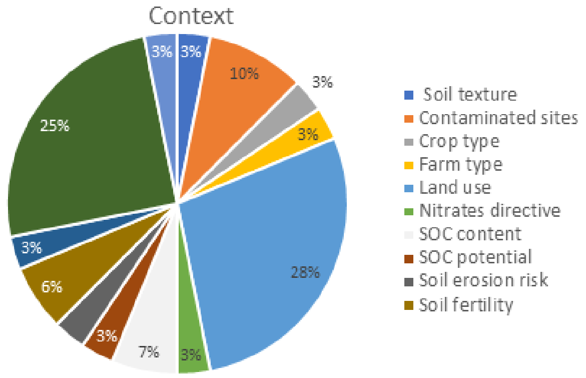
How are references and reference values defined?

The definition of references and reference values can differ per soil quality indicator, and among MS a large variety of definitions exists. Most frequently, the definition is based on (long-term) field experiments (30%), existing literature or databases (28%), or by expert knowledge (22%). Flanders and Norway use spatial data to derive reference values, e.g. soil quality maps, potential yield maps, or soil fertility optimal zones.

Question C1.2

Does your Member State apply different reference values for a specific indicator in relation to context? If yes, describe the different contexts that have been defined, specifying all contexts as applicable in the references that have been developed in your Member State.

In general, MS apply different reference values for a specific indicator in relation to context. In total, 18 MS responded to this question of which 14 responded 'Yes'. The 14 respondents formulated the contexts that have been defined. By far, soil type and land use are used most frequently. Other indicators are based on policies (e.g., nitrates directive, water quality), or on site conditions (e.g., soil erosion risk, contaminated sites).



Question C2.1.

What actual indicator reference values or ranges for soil quality indicators are in use by your Member State?

The MS that responded to this question were: FR, NL, BE-FL, BE-WL, CK, EE, IE, IT, LV, LT, NO, PL, PT, SK, SL, and SE. DK, SP, CH, FI and the UK did fill in the rest of the questionnaire, but were not able to answer this question.

The number of MS that use reference, target and/or threshold values is limited (Table 4). Most MS (9 out of 16) have defined a reference value for C-concentration and P availability (8 MS) is also quite common. An upper and lower limit for soil organic matter is also defined quite regularly, but the C stock of the topsoil or subsoil is only defined by two MS: Ireland and Portugal. France and Ireland have different reference values defined for the topsoil and subsoil C-concentration, and Ireland also differentiated between humic and organic soils, while Slovenia differentiated based on the clay content of the soil. Norway and Slovak Republic have threshold values defined for SOM, however in Norway the threshold value was only valid between 1995 to 2015. It is unknown why this is not valid anymore.

Four MS have defined target values. These were defined values for C-concentration, Ni and Pb, and threshold values for Pb, other PTEs, PCBs, other Organic Pollutants (OP), and salinity.
All respondents, except NO, SK, and SE, have one or more indicator reference value defined for the nutrient status of the soil. Reference values for SQIs related to physical soil parameters are very poorly represented in the EU, because the only countries that have indicators for physical parameters are the Netherlands, Wallonia, Italy, Lithuania and Portugal. Moreover, a very limited number of MS have defined indicator reference values for indicators related to soil water content, physical degradation, salinization, and biological parameters.
There are many soil quality indicators that can be derived from biological parameters. However, the few countries that have defined indicator reference values for biological parameters (France, the Netherlands, Wallonia, Ireland, Poland, Portugal, and Slovak Republic) only defined these values for one or very few indicators (except The Netherlands in the abandoned BISQ program).

While the reduction of soil contamination (e.g., heavy metals) is part of the Strategy for Soil Protection (COM(2006)232) of the European Commission, some countries did not report on the use of indicator reference values for indicators related to chemical degradation (Wallonia, Czech Republic, Ireland, Norway and Slovenia). Latvia has added that criteria regarding heavy metals, PTE and PCBs are prescribed by the Regulations of the Cabinet of Ministers.

Indicators that were missing in the questionnaire, but for which national indicator reference values have been defined are soil sealing (Czech Republic, Italy), ecosystem quality (Denmark), and soil rooting (Italy).

Table 4. Number of MS (out of 16) that have defined reference, target or threshold values for specific soil quality indicators (SQI).

SQI group	SQI	Reference values	Target values	Threshold values
Soil organic matter (SOM)	C-concentration	9	4	2
	Lower limit	5	3	2
	Upper limit	7	3	2
	C-stock (topsoil)	2	2	1
	C-stock (subsoil)	0	0	0
	organic matter quality	0	0	0
	SOM decrease	0	0	1
Soil reaction and sorption complex	pHact	5	0	0
	pHpot	4	2	1
	acidification	0	2	2
	CEC	4	0	0
	BS	2	1	0
Nutrient status	Ntot	4	0	0
	N other	1	0	0
	P available	8	0	0
	K available	6	2	0
	Ca available	2	3	1
	Mg available	5	0	0
	B	2	3	0
	Cu	3	1	0
	Fe	2	2	0
	Mn	3	1	0
	S	0	2	0
	Se	0	0	0
	Si	0	0	0
	Zn	2	0	0
	other	0	2	0
Physical parameters	texture	1	0	0
	stoniness	1	0	0
	porosity	1	1	0
	bulk density	2	1	0
Soil water content	infiltration	1	1	0
	field capacity	1	1	0
	wilting point	0	0	0
	available water capacity	1	0	0
Physical degradation	soil resistance measurement	1	0	0
	soil compaction evaluation	0	0	0
	soil structure measurement	0	0	0
	soil structure degradation	0	0	0
	erosion	0	0	0
Chemical degradation	Al total concentration	0	0	0
	As total concentration	2	0	0
	Cd total concentration	2	1	1
	Co total concentration	0	3	1
	Cr total concentration	1	0	0
	Cu total concentration	2	3	1
	Hg total concentration	1	3	2
	Ni total concentration	2	4	2
	Pb total concentration	2	4	4
	Zn total concentration	2	3	2
	other Potentially Toxic Elements (PTEs)	0	3	4
	Organochlorine pesticides (OCPs)	0	1	3
	Polycyclic Aromatic Hydrocarbons (PAHs)	1	0	2
	Polychlorinated biphenyls (PCBs)	1	2	4
	other organic pollutants (OP)	1	2	4

SQI group	SQI	Reference values	Target values	Threshold values
Salinization	salinity	0	3	4
	electric conductivity	0	0	0
Biological parameters	Soil biological activity (soil respiration)	0	0	1
	Potential Mineralisable Nitrogen (PMN)	1	0	2
	fungal biomass	0	0	2
	bacterial biomass	1	0	1
	C, N microbial biomass	0	0	1
	macro edaphon	0	0	2
	micro edaphon	0	0	0
	meso edaphon	1	0	0
	earthworms	1	0	0
	nematodes	1	0	1
	soil enzymes	0	0	0
	earthworms 2	2	0	0
	Bacterial activity (thymidine-uptake)	1	1	1
	Bacterial diversity (number DNA bands)	0	1	0
	Potential C mineralization	0	0	0
	Functional diversity (AWCD curve gradient)	0	0	0
	Functional activity	0	0	0
	Potworm density	0	0	0
	Potworm diversity (number of taxa)	0	0	0
	Microarthropod density	0	0	0
	Microarthropod diversity (number of taxa)	0	0	0
	Stability (allometric M,N regression)	0	0	0
	Biodiversity (total number of taxa)	0	0	0
	Fungal Biomass	0	0	0
	Other indicators, not included in synthesis by previous stocktake T2.4.2 (EJP SOIL deliverable report D2.2, Pavlů *et al.* 2021)	0	0	0
Indices composed of a combination of soil parameters (specify)	Nematodes, taxa	0	0	0
	Soil organic matter	1	0	0
	Soil Sealing	1	0	0
Additional parameters	PTE / Ba	0	0	0
	PTE / Mo	0	0	1
	TPTE / Sb	0	0	0
	PTE / Se	0	0	0
	OP / Hydrocarbons C5-C10	0	0	0
	OP / Hydrocarbons C10-C40	0	0	0
	OP / Benzene	0	0	0
	OP / TEX (nitramine high explosive)	0	0	0
	OP / COV / Tetrachlorethylene	0	0	0
	OP / COV / Trichlorethylene	0	0	0
	OP / COV / Cis-Dichloroethylene	0	0	0
	OP / COV / Vinyl Chloride	0	0	0
	OP / PAH / Naphthalene	0	0	0
	Hot water extractable carbon (HWC)	0	0	0
	P Stock	1	0	0
	Percentage Grassland	1	0	0
	Livestock Density	0	0	0
	Ecosystem Quality	0	0	0
	Gross soil loss (*E* from RUSLE)	0	0	0
	Soil suitability	1	0	1
	Soil rooting depth	1	0	0

PTE, potentially toxic element; OP, organic pollutant; C10-C40 – petroleum hydrocarbons in the range of C10-C40; VOC, Volatile organic compounds.

Question C2.2.

Can you specify if there is a general method according to which references and reference values have been derived?

Most Partners indicated that there is not a general method, but that multiple methods are used in their country (whether or not in combination with each other) to derive the references and reference values, and that the method used can also differ per soil quality indicator. An overview of the method(s) used by the MS is given in Table 5.

Table 5. Methods used to derive references and reference values for soil quality indicators, specified by country.

Country	Methods
France	Policy, Report, Expert knowledge, National mean, Field observations
Netherlands	Monitoring data in combination with expert knowledge
Flanders	Literature, Modelling, Field observations, Expert knowledge, Feasibility
Wallonia	Modelling , National mean, Geostatistical analysis
Czech Republic	National Systematic Soil Survey, Monitoring, Literature, Expert knowledge
Estonia	Monitoring in combination with expert knowledge
Ireland	NA
Italy	Legislation, Literature
Latvia	Literature
Lithuania	Monitoring, Long-term experiments, Expert knowledge
Norway	Field assessments
Poland	Expert knowledge, Literature
Portugal	Baseline values, Field observations, Legislation, Literature, Expert knowledge
Slovak Republic	Baseline values, Field observations, Literature, Expert knowledge
Slovenia	Expert knowledge
Sweden	Expert knowledge, Field observations

NA, not specified

Question C2.3

What is the precise policy objective for the assessment?

MS were quite consistent in the answer on the question about the policy objective for the assessment of references and reference values. Policy objectives that were mentioned relate to environmental and human health (e.g., reducing leaching of nutrients and contaminants), sustainable agriculture or soil quality. Some countries also use national averages as a reference, which can help identifying areas that potentially harm the environment.

Question C3.1

What evaluation criteria in addition to reference values are in use in your Member state; do evaluations make use of threshold or trigger values, and target values, etc., and if so, how have these been defined?

Besides reference values, 71% of the corresponded MS have also defined so-called intervention values, threshold values, or target/trigger values. However, these values are defined for much less soil quality indicators. These MS defined target values for C-concentration, Ni and Pb, and threshold values for Pb, other PTEs, PCBs, other OP, and salinity. France, the Netherlands, Wallonia, Ireland, Poland, Portugal, and Slovakia have defined threshold values for biological parameters, and Ireland is the only country that specified target values for earthworm numbers and bacterial activity.

Question C3.2

Indicate quantitative values and dimensions for all soil quality indicators used in your national monitoring schemes.

The reference, target and threshold values that were filled in by the correspondents differed much and were difficult to compare. For example, values can be dependent on soil type, soil layer (topsoil versus subsoil), land use, etc. Ignoring such differentiation, a simple comparison of the values for upper and lower limits of references, target and threshold values as specified by MS for C-concentration showed a large variation (Figure 17). The number of MS that have defined reference values for pH and P-availability was also quite high, and therefore these values were also summarized (Figure 18). However, also in these data, differentiations occur. For example, in Wallonia the value for P-availability depend on soil type and pH. Due to these contextual differentiations, we cannot provide reference, target, and threshold values for soil quality indicators based on the collected data. Because of country-specific differentiations, it was also not possible to define reference, target and threshold values per environmental zone (Metzger et al, 2005) or other political or environmental boundaries.

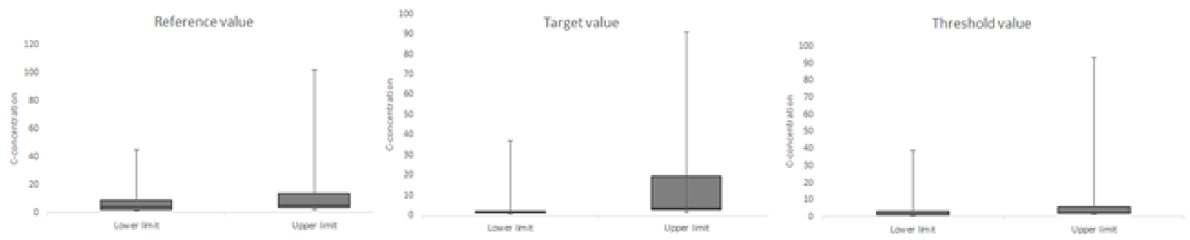


Figure 17. Boxplots of upper and lower limits of the reference, target and threshold values for soil C-concentration as implemented by countries in the SIREN consortium.

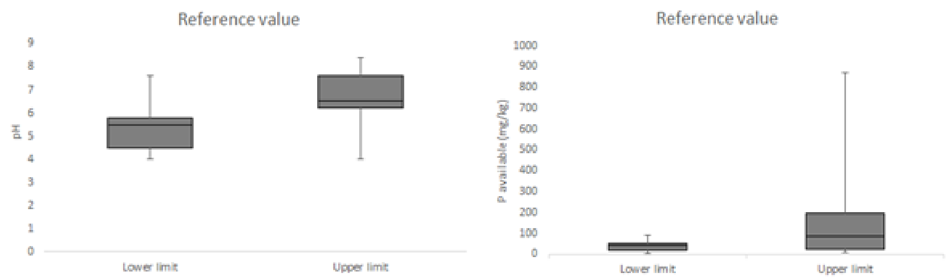


Figure 18. Boxplots of the upper and lower limits of reference values for pH and P-available.

Question C3.3

If "threshold" or "trigger" values are used, what action is triggered and for which actor?

The reason for MS to define intervention, threshold or target/trigger values, can be split into three categories: i) a group that strives for a higher goal in terms of environmental and human health, ii) a group that tries to solve the environmental problems (e.g., erosion, soil sealing, eutrophication) that occur in a region/country, and iii) a group that has defined these values because they had to do it for a compliance programme. The three actors that are responsible for meeting threshold or trigger values are farmers, trade chain, and local/national government.

Question C3.4

If "target values" are used, how have these been related to ecological conditions and to soil functions?

A linkage of target values to ecological conditions for SQIs has not been established in most MS. Lithuania, Slovak Republic and Czech Republic are the only three countries that mention a link to ecological conditions. However, the Czech Republic indicates that ecosystem quality is only defined for nature areas, such as meadows and deciduous forests. For none of the MS is known how target values are linked to ecological conditions in agricultural areas. No clear answer was given to the question if target values are linked to soil functions. Some respondents answered that target values are linked to soil quality, but not to soil functions.

Question C3.5

Have these evaluation criteria been defined for soil quality evaluation in a strict sense, with policy goals being limited to soils-, or is the evaluation using integrated targets across soil, water and climate policy goals at the same time, or integrating across environmental compartments and living resources, balancing for sustainable use and conservation - thus following an 'ecosystem approach'?

Criteria for soil quality evaluation have some clear policy goals. Wallonia mentioned the nitrate directive, water framework directive, and the soil directive as policy goals, but also the Code of Good Agricultural Practices (Portugal) is mentioned. Other countries formulated a more general policy goal, like maintaining/increasing soil organic carbon levels, or soil quality in the context of environmental components, living resources, sustainable land use and land protection. France and Sweden explicitly mention that there is no clear policy goal for soil quality evaluation defined in their country.

Question C4

Which of the soil quality and ES indicators used in your Member State do not have a reference or target value (considering the relevant context of pedo-climatic conditions and the main agricultural production systems in your country)? Is there a particular reason why these have not (yet) been established? What would be needed? If different needs can be specified, which are considered priorities?

Biological parameters are most frequently mentioned as soil quality and ecosystem service indicators that do not have a reference, target or threshold value (Ireland, Flanders, Italy, Lithuania). There are six countries that mention that they do not have defined any reference or target value for soil quality and ES indicators. Reasons for this are the lack in regulations for agricultural soils, lack in data/monitoring, lack in relation between national criteria and ecological approaches, large variation over space and time, and the lacking priority from national governments. To have more reference or target values for soil quality and ES indicators, Partners mention that it is crucial to place it in a socio-economic context and to establish research programs that bridge knowledge gaps from soil quality indicators to soil functions/ES.

Further development of evaluation criteria in the Member State

Question C5

What does your Member State perceive as a current technical, scientific challenge for:

- *the development of monitoring schemes and evaluation criteria for soil quality indicators to evaluate specific policy or management objectives*
- *implementation of indicator references in national policies ?*

Some countries mention the lack in soil monitoring schemes or evaluation criteria on soil quality (e.g., France, Flanders, Switzerland, Estonia). Latvia is currently working on a soil monitoring program, but criteria for the assessment of soil quality indicators to assess specific policy or management objectives is not discussed. Not knowing at which level of detail or accuracy spatial and temporal soil quality monitoring needs to take place, and the lack in a robust, harmonized approach on monitoring soil quality indicators hamper the development of monitoring schemes and evaluation criteria for soil quality indicators. More specifically, the lack in physical and biological indicators together with the missing link between management effects on soil quality indicators makes the development of soil monitoring schemes or evaluation criteria challenging. Sweden indicates that there are many monitoring schemes, but that soil quality is fractioned and weakly implemented in these schemes. The fragmentation of soil-related information among ministries, but also the weak implementation of soil quality in the Common Agricultural Policy (CAP), and the missed opportunity for a Soil Framework Directive are challenges for the implementation of indicator references in national policies. Some countries mention that soil quality monitoring schemes and evaluation criteria are on the agenda, but these developments are only very recent and often have no high priority. Poland questioned whether modelling cannot replace these kinds of intensive (and expensive) monitoring schemes.

Question C6

Do the targets set for indicators differ in view of farming systems, land use and land management; if so, why is such differentiation considered desirable?

Only 13 countries responded on the question whether target values set for soil quality indicators differ in view of farming systems, land use and land management. One reason for not answering this question is because the country does not have target values set for soil quality indicators. The majority of the countries (8 out of 13) makes distinction between farming systems, land use or land management. Reasons for this are simply because soil quality indicators are land use, land management and soil/farm type specific. Other countries do not indicate why there is no distinction made, or they mention that it is desired, but currently not in place.

Question C7

What need for further technical development of indicators and their references and target values is seen in your Member State, particularly regarding the use of indicators for soil quality in the assessment of ES?

For further technical development of indicators and their references and target values some practical and some organisational developments were suggested. The search for an integrated approach that evaluates soil quality and the delivery of ES in a more holistic way (e.g., *Natural Capital Programme*, UK), or a tool (e.g., *Biofunctool*, France) that classifies soil functions is important for understanding and agreeing on the link between soil quality indicators and ecosystem service provision. Denmark remarked that CICES can be further developed by addressing soil degradation parameters. The need for national, regional or even local monitoring programs for agricultural land or pedo-climatic zones was also frequently mentioned as a required development. Latvia indicated that an assessment at the European level would be useful.

Knowledge gaps and other needs for development

Partners were asked to identify knowledge gaps and research priorities that can bridge the gap between soil quality and ES monitoring, specifically for their country. Based on their answers we categorized the knowledge gaps into 12 categories (Figure 19).
Most frequently mentioned research knowledge gaps are related to ‘Background data’ and ‘Indicators and quantification of SQ-ES relationships’. The cause of a knowledge gap in ‘Background data’ are the availability national monitoring schemes to collect data consistently over time and space. Access to data and technical development regarding data collection are sometimes hampering

the availability of background data. Some MS mention the specific lack in data on physical and biological soil quality indicators or techniques to easily obtain these data (e.g., on soil structure).

The knowledge gaps regarding 'Indicators, quantification of SQ-ES relationship' are also often referred to the lack in monitoring schemes. This lack makes it impossible to identify relationships between soil quality indicators and ES. Relationships between SQ-ES are also lacking because of the fragmented knowledge among Ministries. The development of a conceptual framework or definitions were mentioned as a knowledge gap by two MS (Denmark and Norway).

Most frequently mentioned policy and governance knowledge gap is ‘Implement and integrate soil quality monitoring, NEA and NCA’. The lack in integrating or implementing national monitoring schemers are related to the lack in priority or conversion after data collection in different projects/ministries. The latter also indicates the need for harmonization. In Switzerland only qualitative data are collected and these data are used for different purposes (promote management actions).

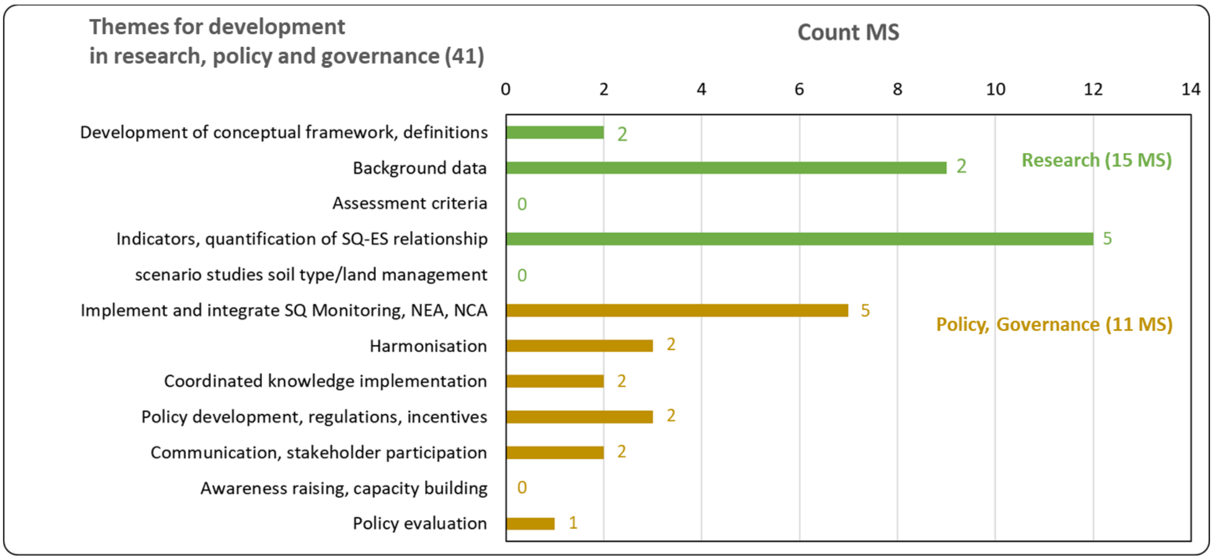


Figure 19. A total of 41 knowledge gaps indicated by the Member States in relation to SQI evaluation criteria, clustered in 12 categories; five categories related to research (green bars) and seven related to policy and governance (brown bars). The numerals at the top of bars indicate the total number of different topics that were specified. Research needs were specified by 15 Partners for their country, and policy development needs were indicated for 11 MS. NEA, National Ecosystem Assessment; NCA, Natural Capital Assessment.

4.5. Questionnaire Section D: Policy relevance and implementation of soil quality-based ES assessment

Questionnaire development: *Maria Viketoft, Jan Bengtsson, Astrid Taylor, Jack Faber*
Analysis and reporting: *Jack Faber, David Montagne*

Summary

Policies dealing with environmental issues can have a long history and in some cases date back significantly before the ES concept was conceived. Member States may have based such policies on related concepts, like soil threats (BE, CZ, DK, IT), soil function (FI), or on soil indicators (IE, SE) potentially linkable to ES assessment, but such policies were outside the scope of our stocktake. Contrastingly, the more recent developments in environmental policy and governance feature the ES concept either as a general headlight (e.g., LV, NO, SK), or as anu instrumental framework to manage specific ecosystems (PT) or landscape elements (BE-WA). There is an increasing interest and progress in implementation of the ES concept. The mainstreaming of the ES concept moreover shows an appreciable diversity in terms of ES considered, the scale of implementation, and land-uses or landscape elements managed, or targeted stakeholders and end-users, demonstrating the potential broad usefulness of the ES concept for managing environmental issues.

Despite the growing interest and broad application potential for the ES concept, and basic scientific expertise being available, the concept has been implemented in policy by few MS only and, when implemented, for a limited number of ES only, and never for the full range (as classified by CICES). The challenges that hinder policy implementation are diverse, and seem highly variable among MS. The top priority is the development and enforcement of national soil monitoring program in MS where such program does not exist or are thought insufficient for ES assessment (BE-FL, BE-WA, CH, LV, LT, NO, SK, SP), the development of a national ES (EE, IE) or NCP (UK) assessment, or the identification of references and target values to interpret ES assessments (FR).
Scientific baseline data is often considered insufficient and trained capacity is unavailable to facilitate immediate policy implementation and legislation. Lack of appropriate indicators (or agreement on which candidate indicators should be used) and quantitative methodologies linking indicators to ES levels seem to be the main obstacles for policy implementation of ES concept and application of soil data in ES assessment. Practical limitations are seen in communication between institutions, education of officials, more projects on the topic for background data and benchmarking, and financial support. Incidentally, lack of harmonisation between different levels and institutions of governance was signalled (UK).

Although not spontaneously identified as an immediate priority by MS, when asked, the harmonisation across Europe of a first tier of soil indicators, did not raise significant opposition, was considered challenging but desirable, and would receive the support (under conditions) of a majority of MS. This is however not the case for a full harmonisation, and in particular reference and target values for SQIs and ES were considered a national matter.

Introduction

This section of the stocktake inquired whether policy and land management in the MS make use of ES assessments that are based on soil data. Also, the current obstructions and challenges for implementation in policy are highlighted.

In the previous questionnaire on soil quality indicators (EJP SOIL T2.4.2., reported in deliverable D2.2), the policy related questions concerned indicators used in monitoring of soil quality. The present questionnaire instead focused on the assessment of ES on the basis of soil quality monitoring data. Transferability and actual transfer of methods to farmers and citizens through participatory science approaches was also briefly examined.

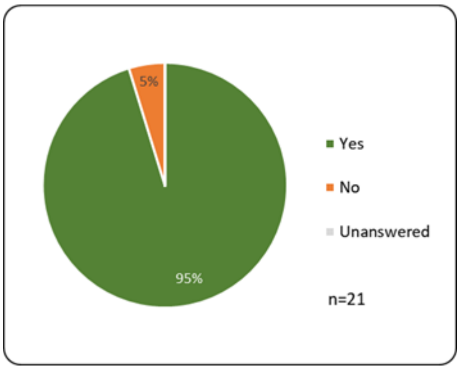
The questions in this Section have been clustered around the following topics:

- Knowledge exploitation and connectivity (EJP SOIL aim)
- Policy relevance of soil quality-ES indicators
- Policy implementation of soil quality-based ES assessment
- Harmonisation and need for contextualisation in the EU, and tiered approach in soil quality monitoring and ES assessment at EU scale
- Participatory science approaches with regards to soil quality monitoring.

Feedback was received from all 21 participating Partners; sometimes individual questions were left unanswered, and the average response rate per question thus was 97,7%. The results are reported in the following, presented along with the original questions from the Questionnaire.
In our analysis we have focused on overview of scientific content and context, rather than explicitly reproducing all Partners' answers; where applicable we have identified Member States by their two-letter code.

Knowledge exploitation and connectivity

Question D1
Is expertise available in your Member State to set up monitoring and evaluation schemes for ES on the basis of soil quality indicators?

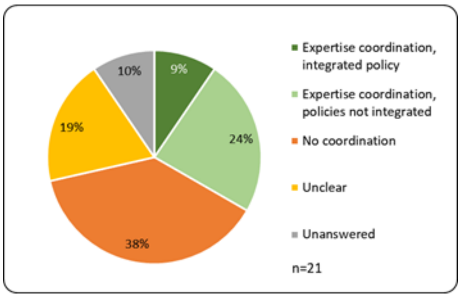


A 95% majority of the participating 21 MS answered to have expertise available for soil data-based ES assessment, at least in academia; it remains unclear to what extent this expertise is present under policymakers. Only one Partner replied "No" (answered by Slovenian Ministry of Agriculture, Forestry and Food).

33% of the Partners have indicated that while adequate expertise is available, this has actually not been implemented in established soil monitoring schemes (FR, BE-FL, UL, NO, PL, SE, CH). We have not distinguished this answer as a separate category, since it is not always clear from the answers or the context whether this may be the case as well for other "Yes" replies. The answer "Yes" does not necessarily imply that expertise has been implemented in actual monitoring schemes. From context and other parts of the Questionnaire it is clear that expertise in SQ-based ES monitoring is in fact most often *not* implemented in monitoring schemes, though in a few MS this is in preparation (FR, NL).

Question D2
How is expertise coordinated? Does this influence the establishment of references and target values with respect to different policy areas; how?

A lack of integration between policy areas may enhance differences in approaches and procedures, and therefore hinder harmonisation or standardisation even at the national level.



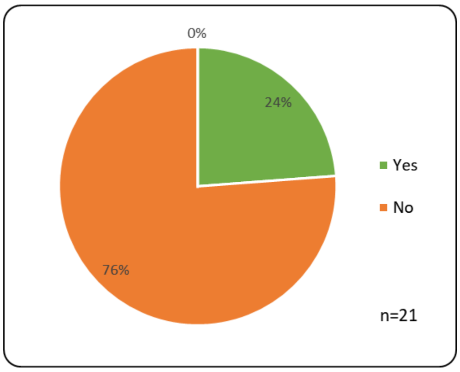
In the 19 MS that replied to this question, most have no integrated coordination of expertise on monitoring and evaluation ES at a national level. This is likely to result from poor expertise outside academia (only two MS). In cases where expertise is coordinated at a national, in half of the times (3 MS) this is shared between ministries of agriculture and environment.

Coordination may also vary with scale of governance: in the UK expertise exists at a regional level in each devolved administration (England, Northern Ireland, Scotland and Wales), where in some areas policies are developed at a regional level and some are at national UK level. This situation was interpreted as “Expertise coordination, policy not integrated”.

Policy relevance

Question D3.1

Is the concept of ES used as a tool in policy-making related to soils? Yes/No



In the majority of MS the ES concept has not (yet) been implemented in soil policy, only five Partners replied “Yes” (IT, BE-WA, NO, PT, SE). The implementation of the ES concept in soil policy however shows an appreciable diversity in terms of ES considered, scale of implementation, land-uses or landscape elements managed or targeted stakeholders. It illustrates the potential broad usefulness of the ES concept for managing environmental issues, but low degree of implementation.

Question D3.2

If yes, which ES of the already listed ES in monitoring (section B, Excel file ES1) are used in policy, and what is the objective?

Considering the five Partners that had indicated that the ES concept is used in policy in their MS (Question D3.1), few mentioned inclusion of the term ES in a legal decree. However, where this refers to soil-based ES and the use of SQ data for assessment of ES, then in all cases this refers to a limited number of ES being addressed rather than a full span ES assessment (e.g., following the CICES classification). Thus, current approaches involve a single ES or perhaps a few ES. However, the term ‘ES’ is not always used in a particular policy area, while the respondent Partner considered the ecosystem function and some associated environmental problem would qualify as an ES approach, e.g., *“the TERM ES is not used. However, the PROBLEM of eutrophication of the aquatic environment (which is affected by the regulating soil ecosystem service,- probably CICES 5.2.2.1) receives much attention and is addressed in a comprehensive monitoring and calculation procedure for providing every year a maximum allowable nitrogen fertilization for all fields...”* (quoted from response DK).

The use of an ES approach in policy and regulations in a broader sense (i.e. focused on more than a single ES) was reported by two Partners (BE-WA and PT), where it is incorporated in landscape management rather than soil management. In Wallonia, a regional legal decree was implemented in 2016 to regulate hedgerow planting, optimizing planting locations based on services they can supply by settling the price of subventions. In Portugal, implementation of CAP policy for the multifunctional cork and holm oak *Montado* agroecosystems was informed by proposing eco-scheme model

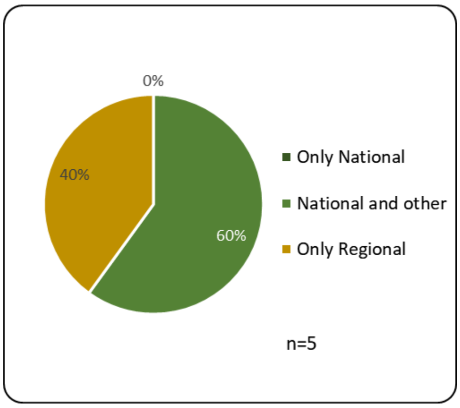
payments based on economic valuation of ES (soil protection, nutrient retention and carbon sequestration) assessed to avoid environmental costs associated with different scenarios for land use change and grazing management. It was not clear whether or how soil quality is included in the two cases as a target for management and policy evaluation.
In other cases single ES approaches are involved (SE: regulation of GHG through carbon sequestration), or approaches including several ES but each considered in separation (IT, NO).

In most recent regulations (mostly after 2015), the assessment of a single or just a few ES is used to regulate the management of specific ecosystems (PT) or specific landscape elements (BE-W), or the ES concept is being introduced in plans and novel programs (e.g. LV, NO, SK). Moreover, some older policies are already based either on related concepts like soil threats (e.g. BE, CZ, DK, IT), soil function (FI), soil health (NO), or on soil indicators (IE, SE) potentially linked to soil services. Finally, a new Latvian Environmental Policy includes the ES concept, but soils are not explicitly linked (LV). Thus it can be concluded overall that there is a growing, wider interest in the MS to use the ES concept in soil policy-making.

Soil-based ES that have been implemented in MS policies comprise:

- Erosion control (but not from an ES perspective), e.g., implemented in rural development plans;
- C sequestration and GHG regulation, e.g. in rural development plans and regional climate strategies;
- Flood protection and water regulation, e.g. in national water policy;
- Water purification and quality;
- Fertilizer application, e.g. regarding nitrates directive, water framework directive;
- Storage, filtering substances: sewage sludge directive, nitrates directive;
- Food supply: crops diversification;
- Hosting biodiversity: soil vitality assessment (rural development plans)

Question D3.3
On what scale are these policies implemented? National / Regional / Sub-regional / Local



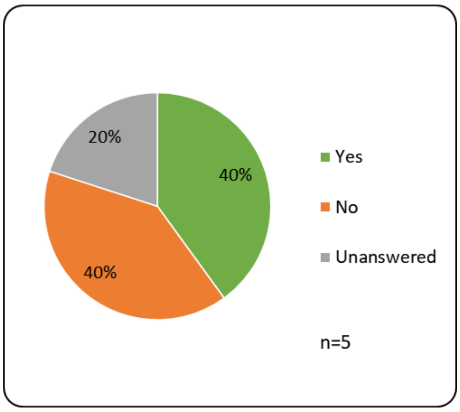
If the ES concept has been implemented in soil policy (5 Partners), this is at regional or national scales; in the three MS where the concept has been implemented at a national scale, it is also at regional scales.

Question D3.4
Are these policies related to specific land uses, e.g. forest and agriculture, or specific landscape elements, e.g. field margins and beetle banks, blue-green landscape veining, riparian zones?

Where the ES concept has been implemented in soil policy (5 Partners), ES-based policies are aimed at agriculture (IT, NO), forestry (IT, SE), specific ecosystems (cork and holm oak *Montado* ecosystems used for forestry and agroforestry in PT), or specific landscape elements like hedgerows in BE-WA or buffer zones in NO (amongst others in this last case). As far as specified in the responses, a focus on

agriculture can be differentiated according to soil type, crop species or management practices (2x), and can be aimed at specific (hedgerows) or multiple landscape elements (3x).
Whereas the main application of the ES concept apparently is in management evaluation to minimize adverse impacts of agriculture or forestry (and perhaps optimising benefits), it seems to be not applied in land use planning and regulating land-use changes (e.g. to prevent soil sealing). It is also surprising that no policy based on the ES concept seems to focus on urban soils (although the Questionnaire did not explicitly ask).

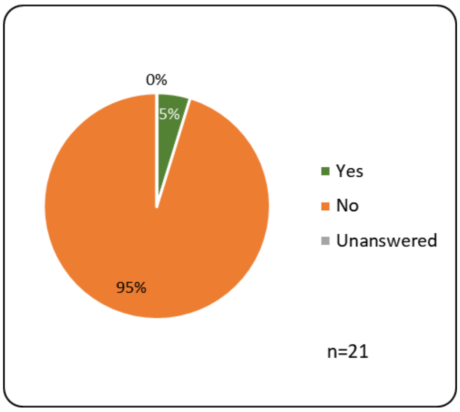
Question D3.5
Are these policies tailored towards specific stakeholders?



Where ES-based policies are tailored towards specific stakeholders (5 Partners), they are tailored towards farmers (IT, NO). When the policies are not tailored towards specific stakeholders (BE-WA, PT), they involve local governance besides farmers (BE-WA) or the whole diversity of land owners and managers independently from their legal status (PT). Science was mentioned once.

Implementation in national soil policy and legislation

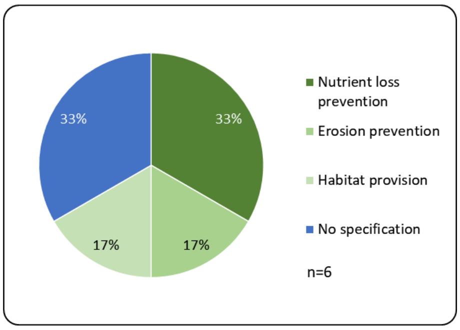
Question D4.1
Is the concept of ES used in national policy or legislation? YES/NO



Only one Partner answered positively that the ES concept has been implemented in policy and legislation in their country (PT). Earlier, in Question 3.1, five Partners indicated that the concept of ES is used as a tool in policy-making related to soils; thus, implementation and legislation can be seen as “in prep”. In comparison to the practical use of the concept as an extension of SQ monitoring, even more Partners (at least 10) have stepped on this path (Question B1). This suggests that in roughly half of the MS things are positively cooking.

Question D4.2

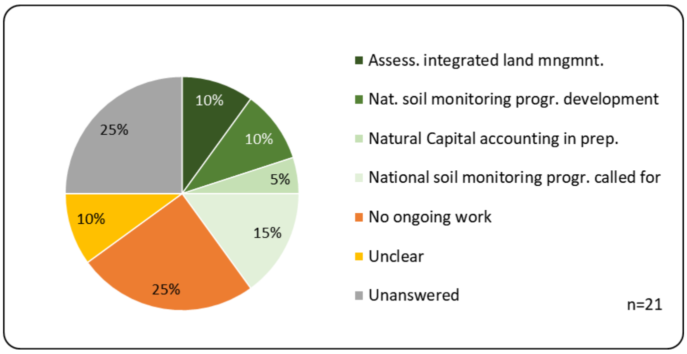
If YES, which ES of the already listed ES in monitoring (section B/C) and how? Are indicators explicitly mentioned in this legislation, including references and target values (please specify which ones)?



Few MS have specified ES in legislation including indicators and target values. The relevant ES that were specified comprise nutrient regulation (prevention of losses), prevention of soil erosion, the provision of habitat.

Question D4.3

If NO, is there any on-going work? What is needed for implementation?

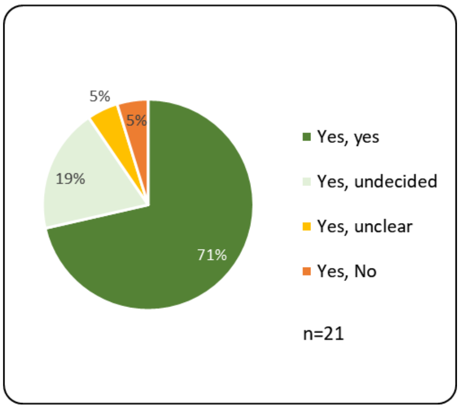


Among the 21 respondents, thus also including MS that *do* use the ES concept in policy, there is on-going work to implement the ES concept in seven MS (LV, NO, PL, SL, SP, SE). In the others, some MS are further developing a soil quality monitoring network (CH) as a first step from which ES physical or economical values may be derived, whereas some others work on a national assessment of soil ES (EE, IE, SK, UK) or on the identification of references and target values to interpret ES assessments (FR). In several MS a national soil monitoring program has been called for, or is being developed, including the identification of ES relevant indicators and definition of reference and target values for such indicators.

Scientific baseline data is often felt missing to facilitate immediate policy implementation and legislation. Lack of appropriate indicators (or agreement on which candidate indicators should be used) seems to be the main obstacle for policy implementation of ES concept and application of soil data in ES assessment. Practical limitations are seen in communication between institutions, education of officials, more projects on the topic, and financial support.

Question D5

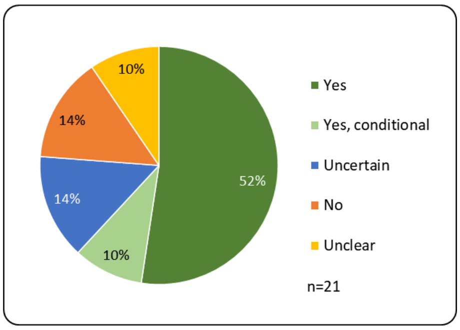
Do you consider that there is a need for soil policy to become more integrated with other areas of EU policy, and do you think that the use of the ES concept could support that?



All Partners consider that EU soil policy should be more integrated with other areas (although one Partner stated that there is no EU soil policy). The majority of MS (71%) considers the ES concept suitable as a concept potentially linking policy areas, but 24% is not sure and refers to "other" approaches such as NCA, or considers the inclusion of a risk approach (soil threats) a prerequisite condition.

Question D6

Do the organisation(s) responsible for the soil monitoring schemes in your Member State consider it useful to link soil quality monitoring to natural capital assessment (NCA) and National Ecosystem Assessment (NEA)? What would be considered advantages or challenges to develop such links?



In general, most MS consider it useful to link soil quality monitoring to natural capital assessment and National Ecosystem Assessment, but appropriate tools are needed (see knowledge gaps). When considered not useful ("No"), this can be because there is no national monitoring of soil quality (NO, SP), unawareness (BE-WA), lack of perceived need (LV), or procedural limitations in governance (UK) in that there are several different organizations involved in soil monitoring and there is differentiation at a regional level.

Advantages (quotes)

Better landscape protection, common system of assessment of natural recourses (especially land)(CZ); improve sustainable use of eroded and peat soils (EE); a major advantage in agricultural land use will be to assess the benefits of investing in more sustainable farming systems, and providing quantitative estimates of the risks to agricultural production from environmental degradations and the associated reductions in ES (PT); integrating the natural capital and the ES concepts in the national accounts, and supplying the national figures with information of the status of ecosystems and the natural environment, are ways of incorporating information about how we affect the environment. If this is not accounted for, we will continue to degrade and deplete important natural resources without it necessarily appearing in the national accounts or showing in the national economy (NO).

Disadvantages and drawbacks (quotes)

Time scales of reporting for SQ and NC vary, and so there are significant challenges for soils data and natural capital data to be connected together. This is a serious issue that is very difficult to resolve (UK). ES approaches used towards land valuations and therefore would get major pushback as most land is privately owned but is required to deliver public goods/ES for wider society (IE).

Knowledge gaps (quotes)

From the feedback to Question D6 the following knowledge gaps can be identified:

- Some important monitoring data are not available for ES assessment, and enforcement of soil monitoring is needed (BE-FL);
- There is a need to understand the role of soil and the linkages better (FI);
- Challenges: more research and data are needed to strengthen the robustness of indicators (IT);
- Soil scientists believe that linking would show the important role of soil in providing ES and functions. This could be facilitated by the development of common EU soil monitoring guidelines (LV);
- To find sustainability indicators (such as biodiversity) to supplement the BNP and the national accounts figures (NO);
- The challenges might be the identification of the soil quality indicators and the associated ES of major interest for policy-making and the clear identification of trade-offs for ecosystems (PT)

Question D7
What in your opinion would be needed to bridge the gap between soil quality and ES monitoring? Can you identify knowledge gaps, research priorities for your Member State?

Very different responses were obtained to this question, both in the nature of development needs that were identified as in the number of development themes that Partners volunteered. The various needs for development returned by the 21 Partners concern either knowledge development and research needs, or policy implementation and governance: 55 specifications of some need were returned, representing 33 different specific needs that were aggregated into 12 themes for development of research, policy and governance as standardised over the different Sections of the Questionnaire (Figure 20). The original topics are presented in Table 6.

Research needs
The most frequently mentioned theme for knowledge development was shared by 13 MS out of 21 respondents. This development need is about establishing robust indicators for soil quality and quantification of their relationship to ES provision, and several kinds of research topics could be recognised under this (Table 6). One of the most recursive needs, the selection of robust indicators used in the computation of ES is more precisely asked to:

- go beyond the classical land use and land cover indicators to quantitatively describe the soil component (EE, PT);
- integrate soil biological indicators (EE);
- be adaptable to different levels of available soil data (BE-FL)
- be mobilizable for the quantification of other concepts such as soil health (NO).

Numerous Partners expressed a need for the establishment of *quantitative* relationships between such indicators and ES (CH, FR, PL, SL, SK). If several approaches are hypothesised to be relevant (expert scoring systems, statistical or process-based modelling, SK), the developed methodologies must clearly target ES (DK), and embrace the largest possible range of ES not only provisioning services (BE-WA). Finally, at least one Partner (SP), claimed for the development of studies dealing with the interactions between ES at the landscape scale.

Thus, in order of priority as determined by number of Partners indicating the topic explicitly, research needs are: indicator development > differentiation for agricultural management > conceptual framework development = gathering background data > development of assessment criteria.

Governance needs
Regarding governance structures and processes the identified development needs are more diverse and less shared in common amongst Partners. However, one quarter of Partners identified a need for procedure harmonisation across regional (UK) or national institutions (NL, LV), or need for increase in capacity and financial resources.

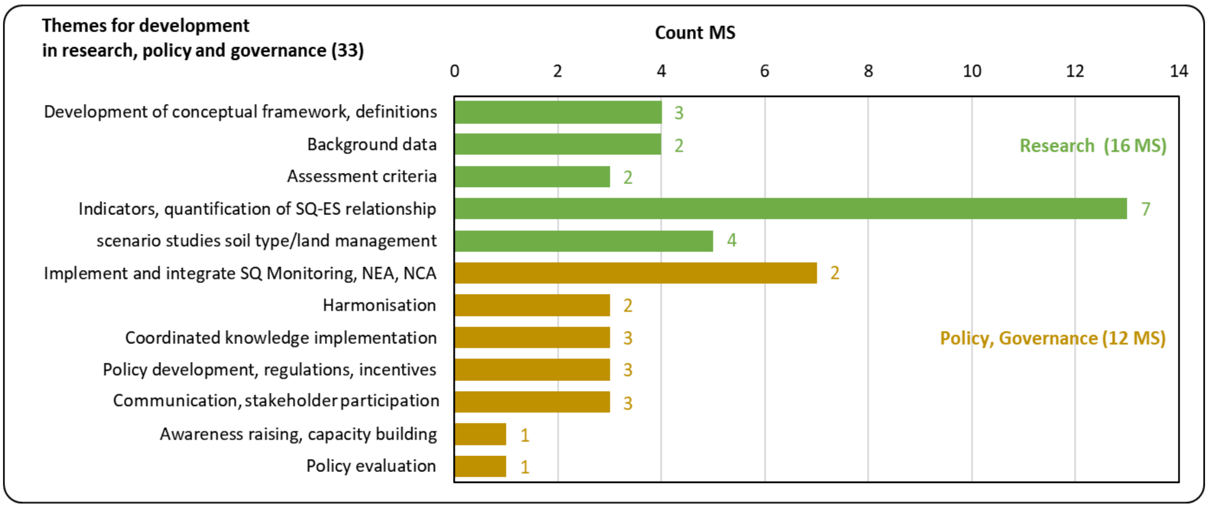


Figure 20. Knowledge gaps indicated by the Member States in relation to implementation of SQ-based ES assessment, categorised under general themes for development in research (green bars) or policy and governance (brown bars). The diversity of specific needs is indicated per theme at the top of the bars (specified in Table D7). Research needs were specified by 16 MS, and 12 MS indicated policy development needs; a total of 50 specifications were received over 33 different gaps.

Another conclusion from the feedback to this question D7 (notably positioned in the Questionnaire preceding a section explicitly dedicated to the topic of EU harmonisation of SQ monitoring and associated ES assessment) is that Partners did not spontaneously identify harmonisation across EU as a need for development, at least not as an immediate priority.

Table 6. Specific knowledge gaps and needs for implementation and further development of policy and governance as identified by the MS.

Sector	Knowledge gaps and implementation needs	Detailed specification
Research	Development of conceptual framework, definitions	• conceptual framework linking soil quality to ES (P1); • "The concept of soil quality might not be too developed/well-defined yet" (SE), "A clarified definition of soil quality must be determined" (CH); • There is no widely agreed definition of natural capital (UK).
	Background data	• Scientific baseline data is missing. "Soil specific functional ranges – including tipping points, thresholds, synergies and trade-offs between ecosystem services across soil types" (IE), Mapping, modelling and activity data insufficient (IE); • Knowledge about the status of soils (IT), Knowledge about the status of Norwegian soils (NO), "An important knowledge gap in Switzerland is the lack of soil data" and maps (CH).
	Assessment criteria	• Assessment criteria for indicators (FR, IE); • Inclusion of SQ indicators in ES analysis with corresponding ES reference values (EE).
	Indicators development, quantification of SQ-ES relationship	• More research is needed to bridge the gap between SQI and ES (SL); • Methods for the calculation of soil quality indicators differentiated for different levels of available soil data (BE-FL); • Inclusion of SQ indicators in ES analysis (EE), Need for real soil properties to map and assess ES in agricultural soils (instead of land cover and land cover changes)(PT), Identify robust key indicators for soil health (NO), "The definition of the key soil quality indicators that represent the key variables is important" (PT), "A national consensus of what soil quality indicators are needed to assess soil quality" (CH), Selecting suitable indicators (IT); • Assess productive as well as non-productive functions (BE-WA); • SQ-ES link differentiated to soil threats (DK); • Soil biological indicators is missing (EE); • A way to calculate/express ES (FR), Quantitative not qualitative approach to ES described by certain indicators (PL), Link soil quality monitoring through appropriately selected models, pedotransfer functions, or expert scoring systems with the evaluation of ES (SK), "Not only the conceptual, but also the quantitative relationships between currently used indicators and soil functions as well as ES are generally under investigated. Therefore, establishing those relationships is of high priority and future studies should particularly address these quantitative linkages" (CH); • Detailed knowledge on the interactions that take place at landscape level (SP).

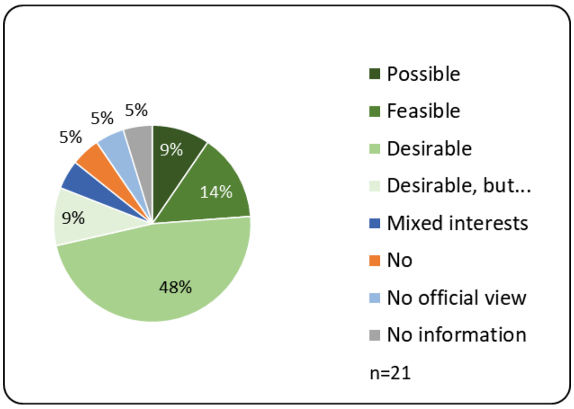
Sector	Knowledge gaps and implementation needs	Detailed specification
	scenario studies soil type and land management	• SQ-ES link differentiated to management impact (DK); • Soil specific functional ranges related to management (IE), Key soil indicators must have sensitivity to reflect the multi-dimensions and the complexity of a soil with agricultural practices (PT), Detailed knowledge on the abiotic and biotic processes occurring under different agronomic and forestry practices(SP); • Assessment of Integrated Land Management (IE); • Knowledge about the status of best practices/measures (NO);
Governance	Implement and integrate SQ Monitoring, NEA, NCA	• Monitoring program initiation (BE-WA), Implementation of SQ and ES monitoring (FI), Bigger financial support (LV), "Financial resources to carry out different soil monitoring packages" (LT), Increased research funding (IT), "Just starting to establish initiatives for measuring soil quality at a national level" (SP); • Spatial/temporally harmonised monitoring scheme (P13);
	Harmonisation of indicators and approaches	• Sharing suitable indicators (IT); • Lack of unified systems or approach in country among institutions (LV), "Need to agree on a common approach across different devolved administrations in the UK" (P26).
	Coordinated knowledge implementation	• The various skills exist, it is necessary to federate them around a common project (BE-WA); • Lack of specialists in country (LV); • Disconnection and lack of exchange between soil scientists and environmental scientists that assess ES (PT).
	Policy development, regulations, incentives	• Integrated policies from collaboration between ministries (NL); • Legislation regulations (LV); • Develop existing incentives and establish new incentives (NO)
	Communication, AKIS integration, stakeholder participation	• Whole system - AKIS integration (IE); • Extension services and general info on soil health (NO); • "How to make these measures and overall assessment clear at the practical (i.e. farm) level must be clarified" (CH).
	Awareness raising, capacity building	• Expertise training (LV).
	Policy evaluation	• Evidence of efficacy and socio-economic outcomes evaluation (IE).

Note: 'Identify robust key indicators for soil health' was categorised under Research (bottom up), but is a policy need as well (top down).

Harmonisation and tiered approach

Question D8

What is the view in your Member State on harmonisation of indicators, ES assessment, and references or target values, or at least a common structure of using such values across the EU? Is this considered possible / feasible / desirable? Would you like to elaborate on challenges and opportunities?



A 70% majority in MS consider harmonisation desirable, but some are explicitly opposed to implementing target values similar across EU. This is a misunderstanding of our suggestion, where we meant that in a tiered approach similar indicators would be used along standardised methods. Target values would be derived by harmonised methods as well, but may vary very well according to soil type, climate and agricultural systems. When perceived in these terms, no opposition was observed in the MS feedback; many Partners specified the desirability of harmonisation if allowing for regional differences.

Challenges:

- Pan-European ranges/thresholds for sustainability indicators require context specificity but also context specific management etc.
- Pan-European of labs/measurement etc. harmonisation is "a big job";
- Possibly the social barriers must be also overcome;
- Our challenges are: soil competences scattered in diverse institutions and funding constraints;.
- NO questioned suitability of Pan-European indicators, suggesting priority for indicators at the national level. SK would agree to European harmonisation, but methods should remain decided at a national to facilitate long-term data comparison in national monitoring schemes. CH aims to develop monitoring and assessment at the national level first, before considering European harmonisation feasible. While for different reasoning, the latter two responses were both interpreted as "Desirable, but".

The Global Soil Partnership (GSP) has addressed as one pillar of action the harmonisation of soil quality monitoring: harmonization of methods, measurements and indicators for the sustainable management and protection of soil resources, including the harmonisation of methods, indicators and evaluation methods (VonHögen-Peters and Blauw 2019). A means to implement harmonisation in soil monitoring may be to develop a tiered approach, which is commonly used in, for example, environmental risk assessment and by the IPCC. A tiered approach can help in standardizing methods and procedures, and improving general applicability across Europe.

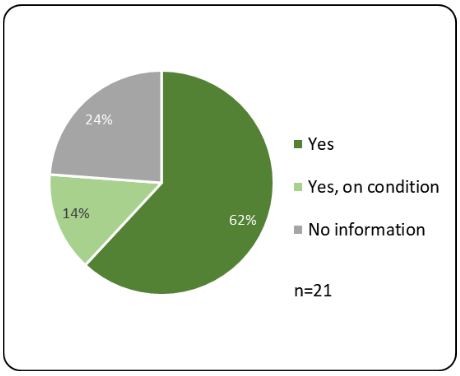
A tiered approach in soil quality assessment could look like this:

1st Tier	Involves general, uniform indicators, applied across EU (="minimum dataset") (e.g. SOM, bulk density, and other indicators already implemented by most nations). This tier may be a harmonised component of soil monitoring across EU.

2nd Tier	More detailed monitoring studies, using additional indicators to be selected by Member States themselves in view of their specific needs and objectives (thus leaving room for regional differentiation within EU.

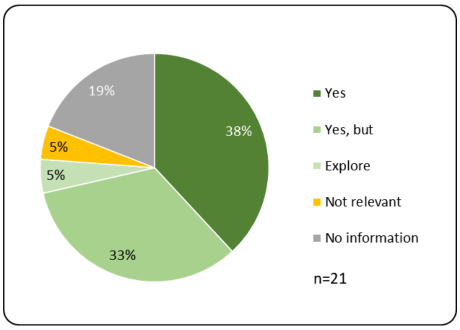
3rd Tier Involves modelling, supplement measurements, providing more detail at regional and lower scales and supporting tailor-made, site-specific decision making and management if needed.

Question D9.1
Would the agencies responsible for soil quality monitoring in your Member State be supportive of a development of such a stepwise approach at EU level?



None of the MS opposed to a tiered approach, while three-quarters are positive. A fifth of the MS phrased conditions to implementation of such an approach. The suggested tiered approach is considered possible if there is sufficient (national) influence on the way of working to this approach and the interpretation of the results. It will only work if it is in dependence of existing monitoring systems and indicators, and MS can opt for a specific level (tier) which is the best fit and desired for the MS, as soils, climate and agricultural systems differ per country and even per provincial region. Other conditions involved the availability of data, and a harmonised approach to higher tiers.

Question D9.2
Would the agencies responsible for soil quality monitoring in your Member State agree that a Tier 1 approach would benefit from a harmonized methodology and standardisation of methods?

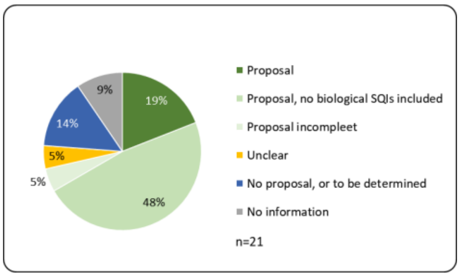


Many MS would support harmonisation and standardisation of a first tier, but indicate that it will require time and resources to switch and keep data comparable by comparing methods. Also, evaluation criteria should remain specific for MS conditions and objectives. One MS replied that they would embark on standardised tiers after national development of SQ monitoring, another considered the question not relevant. An interesting suggestion was to fill Tier 1 with extension SQIs in LUCAS.

A view that was also expressed is that full harmonisation may be unrealistic. We consider that whatever is commonly agreed to be realistic should be the SQIs to make up the 1st Tier and MS can elaborate to specific needs as they see fit. Another suggestions was to follow INSPIRE guidelines for data specification.

Intro to Question D10
The preceding stocktake T2.4.2. has shown that the top most often applied soil quality indicators across all participating countries are organic carbon concentration in soils and its changes in time, soil macronutrients (N, P, K) and micronutrients (Cu, Mn) contents, soil pH, cation exchange capacity and base saturation of soils, soil texture and bulk density, and contamination with potentially toxic elements, especially Cd, Co, Cr, Cu, Ni, Pb and Zn.

Question D10
If a tiered approach would be implemented across EU or in your country, what would be your suggestions for soil quality indicators to be included in a first tier (i.e. potentially harmonised across EU) minimal dataset? Your answer may differ from the above mentioned indicators, which are the ones currently most frequently used across Member States.



Two-thirds of the MS answered this question with a proposed shortlist of SQIs they see fit for a minimum dataset to be obtained in first tier SQ monitoring. Notably, half of the responses did not include any biological SQI. It is unclear from the answers whether this reflects the current developmental state of MS monitoring schemes, which most often comprise chemical and physical SQIs only (Pavlů *et al.* 2021), or this is really reflecting a considerate choice by these MS to not assess biological aspects of SQ (and their relationship with ES) as part of basic monitoring.

It comes as no surprise that the most frequently proposed SQIs (Figure 21) are amongst the top-10 indicators most used by MS, as shown by the preceding T2.4.2 stocktake (EJP SOIL deliverable D2.2).

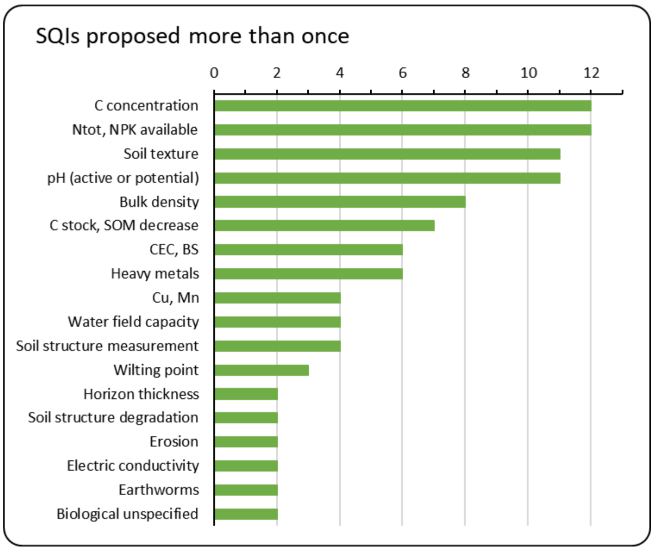


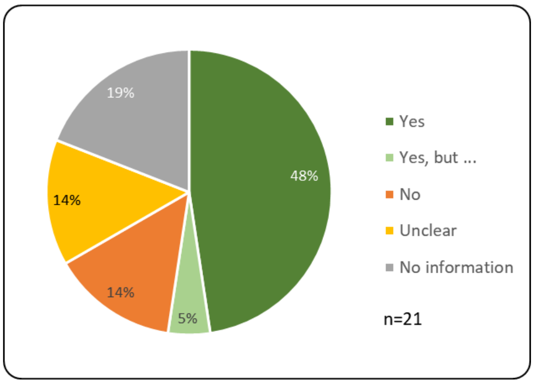
Figure 21. Ranking of soil quality indicators (SQIs) by number of MS that would suggest the particular indicator for application in a first tier if a tiered approach for soil monitoring were to be implemented. SQIs mentioned by one Partner only are not represented

Soil texture is strictly not an SQI (not responsive to internal or external drivers) but an inherent soil condition, and while not proposed by all MS here for first tier assessment, it is included by all MS in their national SQ monitoring schemes (EJP SOIL deliverable D2.2). Soil texture is key in understanding soil communities and soil functioning, and may explain a large proportion of the variance of dynamic chemical and biological parameters (e.g. Salomo *et al.* 2014).

Soil biodiversity indicators to be included in a first tier were suggested by four Partners (19%). This referred to earthworms (NL, IT), microbial biomass (NL), microarthropods (QBS-ar, Menta *et al.* 2018)(IT), or no indicator has yet been selected but the intension is explicitly there (NO, SL).

Some comments are of special interest:
- DK stressed a need for subsoil data to be included in all tiers.
- Soil compaction is very relevant in the UK and soil bulk density could be used as proxy for compaction.
- Regarding soil structure, one suggestion developed in Switzerland to target organic carbon for soil management determined an SOC to Clay ratio of 1:10 is an indicator value of reasonable soil structural quality (Johannes *et al.* 2017). Lower thresholds and optimal value ratios have also be described. However, this is not currently used in national legislation, and would need to be discussed further before this is suggested in an official capacity.

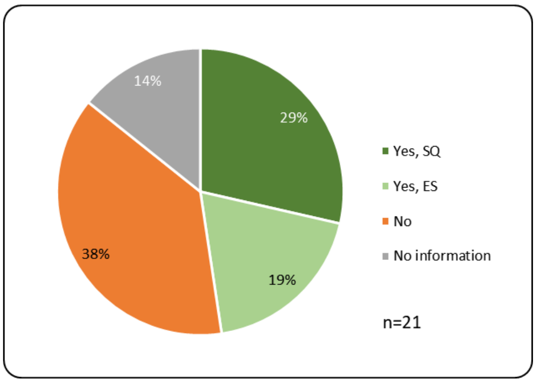
Question D11
Would these SQ indicators also suffice for ES assessment, or would you prefer other indicators for that purpose? Which indicators should then be in a first, harmonised tier?



Half of the Partners (11 in 21) agreed that these soil quality indicators (and soil texture as a key site condition parameter) are sufficient for ES assessment in a first tier. Two Partners (CZ and LT) considered the introduction of climate, land-use or other soil data (soil type, soil horizon stratification), whereas three Partners considered it at least difficult, if not doubtful, to assess ES from soil quality indicators only due to insufficient financial resources to monitor all the necessary SQI (LV), or to the methodological challenge to link soil quality indicators with ES levels (PT, CH).

Participatory science

Question D12
Are there any ongoing participatory science approaches with regards to monitoring of soil quality or ecosystem services in your Member State? Please, indicate which indicators are monitored, and the groups in society that are involved?



Half of the Partners (10 in 21) are using participatory science approaches to monitor soil quality (6 Partners) or ES (4 Partners). These approaches are very diverse in terms of kind of data, of spatial and temporal representativity (from cumulative approaches at the national scale to site-specific ones at a local scale), or in the audience targeted. When ES are concerned, several ES seem to be assessed at the same time. These are however "general" ES, not specifically soil-related. The approaches are generally based on "expert" judgment (BE-WA, PT) and involve stakeholders such as politicians, scientists, and administrators. When soil quality indicators are concerned, most of participatory approaches have been focused on the assessment of biological activity through demonstration projects involving the degradation of tea bags or cotton underwear (a worldwide experiment “Soil my undies”, joined by CH and NO) and earthworm inventories (FR, NL). These approaches are characterised by citizens involvement. One approach (DK) is more specifically involving farmers, and is aimed at storing farm soil analysis data; it was not clear whether such data would be available for national assessment and reporting. Such databases are likely to exist in other countries, particularly with commercial labs that perform farm soil analyses (e.g., LV, NL), but this was not reported by Partners.

5. POLICY-RELEVANT SQIs; BACKGROUND ANALYSIS

Maria Viketoft, Antonio Bispo, Gregory Obiang-Ndong and Jack Faber

Summary

For long there has been no integrated soil policy, but the EU has in November 2021 adopted a new soil strategy for 2030 that will push for development of soil quality assessment at national and pan-European level. The soil quality indicators (SQIs) to use are generally not directly specified in e.g. agricultural and environmental policy documents, but indicators are certainly needed to assess the status of the environment and monitor progress towards policy objectives. Therefore, suitable SQIs need to be selected and developed. A range of possible SQIs has been suggested in scientific literature and by European research projects, and is reviewed in this chapter. The importance of including chemical, physical and biological indicators is highlighted, although at the moment the implementation of biological indicators in national soil monitoring is scarce and limited. Overall, there is a lack of conceptual frameworks linking SQIs and ES assessments and methods (e.g. ecological production functions) to link SQIs to soil functions and ES supply. This is urgently needed for wider implementation of national ES assessments.

In this chapter we have compiled a summary table of SQIs in order to select the most policy-relevant SQIs that are, besides being suggested by science, already implemented in several European countries, requested by policies and favoured by stakeholders. We suggest a tiered approach for SQ monitoring, where the main recommended indicators (which are currently used, validated by the literature and needed for policies) are harmonised in a first tier, with consecutive tiers to obtain more detailed and specified data at finer spatial scales.

5.1 Introduction

Complementary to the stocktake amongst MS presented in the previous chapter, this chapter presents a background analysis on policy relevancy of indicators for soil quality and ecosystem health (here: soil-based ES), based on literature review, national ecosystem assessments (NEAs), approaches by global and European institutions, and key European research projects. We provide an overview of developments in European and global policies that relate to and can affect soils, and we enumerate the data needs and associated SQIs that are called for by these policies. We also summarize the range of suggested SQIs by some international stakeholder institutions and European research projects, as well as the parameters used in national regulations gathered from EJP SOIL Partners during the preceding stocktake T2.4.2 (Pavlů *et al.* 2021) performed during first year of EJP SOIL. In addition, we present approaches to the development of evaluation criteria for SQ data, and how SQ data may be used in the assessment of ES and NC. Thus, in this chapter we establish current views on best practices, and perspectives for implementation and harmonisation.

5.2 Methods and Approach

Current international and EU policies

International and EU relevant policies and initiatives were reviewed to identify the soil indicators recommended or needed. The outcome was summarized in this chapter.

Current national regulations within EJP SOIL countries

Some participants in the SIREN project are directly involved in WP2 and WP6 of EJP SOIL, and had access to reports and documents produced there. Activities of these WPs relevant for SIREN have been summarized in this chapter.

Scientific literature

Conceptual frameworks

The systematic review regarding conceptual frameworks was performed in May 2021 using the Web of Science (WoS) Core Collection (https://webofknowledge.com/). Peer-reviewed articles published in English between 2005-2021 were selected. Searches focused only on Topic (title, abstract, author keywords, and "Keywords Plus") and were performed using the following query: TS = ("Ecosystem service*" AND ("soil quality" OR "soil health")). Although our main objective was to identify relevant conceptual frameworks linking soil quality indicators and ES assessment in the context of agricultural soils, our search did not include keywords related to agricultural soils or landscape (e.g. "agro*" OR "agri*" OR "farm*"). We made this choice so as not to rule out relevant conceptual frameworks that, while not directly applicable, could still be adapted to the context of agriculture. For the considered period (2005-2021), the total number of articles retrieved from our search query was n=508. This set of articles were manually screened using their titles, abstracts, and figures. Not conceptual articles were excluded.

SQ and ES indicators

The literature search regarding SQ and ES indicators was cost-efficiently aimed to retrieve relevant review articles and was performed in August 2021 also using Web of Science. We chose to restrict our search to review papers published in the last 10 years (2011- August 2021), as we postulated that these would have included prior reviews. The search terms used were "soil quality indicator* AND ecosystem service*", "soil quality indicator* AND policy*", and "soil* AND indicator* AND ecosystem service*", and the searches were further refined by Document type (Review articles) and Research Areas (Agriculture). This resulted in 41, 23 and 84 articles in the respective searches, with quite some overlap. This set of articles was manually screened using the titles and abstracts, which resulted in the final selection of 17 review articles. In addition, we manually included three articles that we were aware of but had not been included in the search results. During the process of reading the review papers, additional articles referred to in the review papers were also reviewed for more detailed information regarding certain aspects. During the reading of the papers, extra focus was the identification of indicators that are widely applied in SQ assessments, and the linkage of such indicators to functions and ES. The search may not have been exhaustive for references, thresholds or target values to these indicators.

EU Projects

The list of projects, programs or platforms having generated or used soil information at European level or beyond compiled within WP6 of EJP SOIL (Annex 1 in van Egmond and Fantappiè 2021) was used as a base for selecting projects relevant to SIREN. Three projects were chosen (ENVASSO, RECARE and LANDMARK) and for these projects publicly available reports and scientific articles were reviewed.

National Ecosystem Assessments

We focused on European national ecosystem assessments (NEA) published after the Millennium Ecosystem Assessment (MA 2005). We followed the selection methodology of Schröter *et al.* (2016) and only considered NEAs that had a (close to) national approach and that assessed ecosystems or ecosystem services. For the period 2005 to 2015, we relied on the eight NEAs identified in the review article by Schröter et al. (2016). On the basis of the selected methodology, the latter excluded the Swiss assessment (Staub *et al.* 2011). Nevertheless, in concordance with Schröter *et al.* (2011) we point out that Staub *et al.* (2011) present a solid conceptual framework with suggestions for national indicators. To cover the time from 2015 onwards we searched for NEAs using the following sources:

- Information from the EU Mapping and Assessment of Ecosystems and Their Services (MAES) working group (Maes *et al.* 2020) available at JRC Publications Repository - Mapping and Assessment of Ecosystems and their Services: An EU ecosystem assessment (europa.eu)
- The webpage of BISE - Biodiversity Information System for Europe (europa.eu). The Biodiversity information system for Europe is a partnership between the European Commission and the European Environment Agency. Here, we consulted the 26 country profiles at Countries (europa.eu) to view the national activities on MAES.
- The IPBES Catalogue of Assessments on Biodiversity and Ecosystem Services (*http://* catalog.ipbes.net);
- Google Scholar using the search terms "*national ecosystem service assessments in Europe*" OR "*mapping and assessment of ecosystem services in Europe*" OR *"nationwide monitoring of ecosystem services in Europe"*.

Stakeholder institutions

Participants of the SIREN project are also directly involved in some stakeholder institution activities (i.e. JRC and FAO), and relevant on-going work and reports are summarized in this chapter. From other institutions, publicly available reports have been reviewed and there have been discussions in direct personal contact (EEA, IUCN, GSBI, IPBES).

5.3 International and EU policies

Various policies may directly or indirectly impact soils. Of course, all agricultural policies affect soil management and therefore soil quality. Several environmental policies on climate (e.g. carbon stocks, and GHGs emissions from soil), water (e.g. soil regulates water quality and fluxes), biodiversity (e.g. above and below ground abundance and diversity are driven by soil), waste recycling (e.g. composts and sludges are spread on soils as amendments or fertilizers) and energy (e.g. bioenergy depends on soil resources availability and quality) need to consider soil status and availability. Finally, human well-being also depends on soils for food, housing and health (e.g. health benefits of antibiotics, health risks from soil contamination). This section is a brief enumeration of global UN and EU policies that will require consistent soil data acquired by means of commonly applied SQ indicators.

United Nations Sustainable Development Goals

The Sustainable Development Goals (SDGs)[10] were formally adopted by the heads of State and Government of the member states of the United Nations in 2015 in the context of a global Agenda for Sustainable Development by 2030. Strong links can be drawn between the SDGs and soils, as some can be directly connected[11] to soil quality and soil management (Keesstra *et al.* 2016, Bouma *et al.* 2019):

- SDG 2: End hunger, achieve food security and improved nutrition, and promote sustainable agriculture;
- SDG 3: Ensure healthy lives and promote well-being for all at all ages (non-communicable diseases, mental health and environmental risks);
- SDG 6: Ensure availability and sustainable management of water and sanitation for all;
- SDG 13: Take urgent action to combat climate change and its impacts;

[10] https://sdgs.un.org/goals

[11] Note that SDG 7 (Ensure access to affordable, reliable, sustainable and modern energy for all), SDG 11 (Make cities and human settlements inclusive, safe, resilient and sustainable) and SDG 12 (Ensure sustainable consumption and production patterns) are also indirectly connected to soil.

- SDG 15: Protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.

Reporting on these SDGs to identify progresses and/or remaining gaps will require several soil indicators to report and monitor soil status and trends (see Table 7), even while soil indicators are not directly specified in the documents. At international level, several conventions also require information on land and soils, e.g., the UN Convention to Combat Desertification and the UN Framework Convention on Climate Change that both ask for an indicator on soil carbon stocks. Recently, FAO-ITPS developed and proposed a protocol for the assessment of sustainable soil management (FAO-ITPS 2020), and a minimum dataset of indicators was requested (see Table 7).

United Nations Framework Convention on Climate Change

Under the Kyoto Protocol, Parties can elect human-induced activities to be included in its accounting for in meeting the Kyoto Protocol's emission targets. These activities are related to Land Use, Land-Use Change and Forestry (LULUCF), specifically, forest management, cropland management, grazing land management and revegetation. Activities in the LULUCF sector can provide a relatively cost-effective way of offsetting emissions, either by increasing the removals of greenhouse gases from the atmosphere (e.g., by promoting C-sequestration in agricultural soils), or by reducing emissions (e.g., by mitigating N-emissions from agricultural soils).

There is a clear need for validation of sustainable management practices (UNFCCC 2016). EJP SOIL has adequately recognised this priority, and is currently facilitating various research projects through internal and external calls dedicated to this topic.

In addition to further scientific underpinning, the development of climate change mitigation strategies also needs significant elaboration along the socio-cultural-economic dimension, particularly by involvement of stakeholders. During the 2021 COP26 in Glasgow, the meeting of the Parties to the Paris Agreement was presented with the report of the forum on the impact of the implementation of response measures. In the exploration of approaches to inform the development and implementation of climate change mitigation strategies, plans, policies and programmes that maximize the positive and minimize the negative impacts of response measures, the decision was drafted to include as a first recommendation pertaining to activity 1 of the workplan to "Encourage Parties to engage relevant stakeholders at each step of the process of designing and implementing climate mitigation policies and policies to achieve sustainable development including through social dialogue, when possible and subject to national circumstances. The relevant stakeholders, among others, include workers, employers, organizations, academia, public and private sectors, women, and civil society" (UNFCCC 2021).

European Green Deal

The recently adopted European Green Deal (EGD) includes a set of policy initiatives agreed by the European Commission with the overarching aim of making Europe climate neutral in 2050. This ambitious package includes measures on biodiversity, agriculture (Farm to Fork strategy), reduction of pollution (zero pollution ambition), circular economy, and energy (Figure 22) (EU 2019). Even while not explicitly mentioned in this document, soils appear to be a key and cross cutting success factor as being a:

- source or a sink of carbon and other GHGs (N_2O and CH_4)
- support to biomass production for food, bioenergy and biomaterials
- receptor area for recycling materials as composts and sludges
- reservoir of biodiversity, yet underestimated
- sink for contaminants

Montanarella and Panagos (2021) stressed the point that soils have to be included as a key element of the proposed EGD as being the foundation of agriculture, playing an important role in mitigating greenhouse gas emissions and being a large biodiversity pool. They claimed for developing a coherent sustainable soil management framework given the necessary trade-offs between contradicting goals and targets. According to them, such strategy should be supported by an observatory (EU Soil Observatory - EUSO) able to monitor, report and verify the relevance of policies. A soil dashboard should be created indicating the state and trends of a broad range of existing and new soil indicators reflecting diverse policy drivers and concerns (compaction, salinization, pollution, biodiversity) relevant to the various Commission services related to soils (e.g. DG ENV, DG CLIMA, DG AGRI, DG SANTE). Such development will require the selection and the development of indicators.

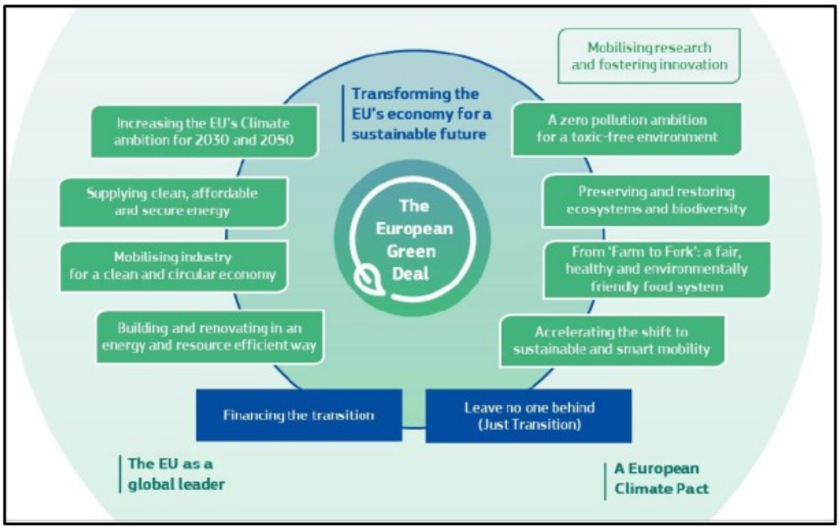


Figure 22. The European Green Deal.

Common Agricultural Policy

Among all EU policies, the Common Agricultural Policy (CAP) is certainly playing an important role in managing natural resources as soils. The prevention of soil erosion and improvement of soil management, water management (quantity and quality), restoring, preserving and enhancing biodiversity (landscapes, habitats) constitute important elements of the CAP, which will implement from January 2023 higher environmental and climate ambitions, aligned with the Green Deal objectives.

Soil information data are already needed and included in the CAP dashboard[12] :

- the quantity of soil organic matter
- a map on the risk of soil erosion
- information about crop diversity.

The dashboard also includes other graphs related to CAP interventions directed to soil quality: the share of agricultural land under rural development contracts includes actions to soil management and to prevent soil erosion. The greening obligation on crop diversification (expressed both in number of beneficiaries and areas) aim to keep an overall minimum diversity on arable land. EU countries will need to report (i.e. collect, organize and analyse soil data) on both issues at the national level.

[12] https://agridata.ec.europa.eu/extensions/DashboardIndicators/Soil.html?select=EU27_FLAG,1

EU Soil Strategy 2030

The EU Soil Strategy for 2030 replaces the former Thematic Strategy for Soil Protection from 2006. The new Strategy sets out a framework and concrete measures to protect and restore soils, and ensure that they are used sustainably. The Strategy is a key deliverable of the EU Biodiversity Strategy for 2030, and will contribute to the objectives of the European Green Deal. It sets a vision and objectives to achieve healthy soils by 2050, with concrete actions by 2030. It also announces a new Soil Health Law by 2023 to ensure a level playing field and a high level of environmental and health protection. To facilitate juridical elaboration, a clear definition of the concept is adamant and will need focussing on a specific European understanding[13].

The EU Soil Thematic Strategy

The Thematic Strategy for Soil Protection identifies the key soil threats in the EU as erosion, floods and landslides, loss of soil organic matter, salinisation, contamination, compaction, sealing, and loss of soil biodiversity. It consists of a Communication from the Commission to the other European Institutions (EC 2006a), a proposal for a framework Directive (EC 2006b), and an Impact Assessment (EC 2006c). The Strategy is built on four pillars, namely awareness raising, research, integration, and legislation.

Following the withdrawal of the legislative proposal due to the opposition of a minority of countries in the Council, in 2015 the Commission set up an Expert Group mandated by Member States to reflect on how soil quality issues could be addressed using a targeted and proportionate risk-based approach within a binding legal framework. Given the cross-sectoral nature of soil issues and the diversity of environmental and socio-economic pressures and governance conditions across Europe, many different policy instruments at EU and Member State level exist that either explicitly reference soil threats or soil functions, or implicitly offer some form of protection for soils. However, a report analysing existing soil protection policies and measures, and identifying key gaps in soil protection, highlighted that EU level policy instruments lack a coherent and strategic policy framework for adequate protection of soils (Frelih-Larsen *et al.* 2017).

Soil Health and Food Mission Board

The European Commission has identified five missions, which are targeted initiatives which include research, innovation and other measures to tackle societal challenges. One of these concerns soil health and food. The main goal of this mission is that by 2030 at least 75% of soils in each EU Member State are healthy, or show a significant improvement towards meeting accepted thresholds of indicators, to support ES (Veerman *et al.* 2020). The Mission Soil Health and Food has recommended the measurement and monitoring of soil health indicators and the development of agreed/shared thresholds depending on soil type, land use and climate zone to support EU policies as the recently adopted EGD. The Mission proposed to use eight indicators to assess current status and track change, and five of these include soil indicators; soil pollutants, soil carbon, bulk density, soil biodiversity and soil nutrients together with pH.

From the overview presented in Table 7 it is evident that soil organic matter (soil carbon) is the most often required indicator parameter in European and global policies. Many other parameters will be needed in combination, however, from chemical to biological measurements, to be able to monitor progress in the various policy areas, especially when featuring competing claims. As developed in the following section, countries differ in the degree of organizing the monitoring of soils at various spatial scales, and this will require a significant effort to comply with international policies.

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[13] Irrespective, for example, of a traditional understanding and implementation in environmental policies that was more narrowly focussed on productivity of agricultural soils, as is common in the USA (Moebius-Clune *et al.* 2016, Rinot *et al.* 2019, Lehmann *et al.* 2020), or the prevention and remediation of soil contamination.

Table 7. Summary of soil data and derived indicators required by UN and EU policy frameworks.

Policy/initiative	Data/indicator needed	Spatial extent
UN Convention to Combat Desertification	Land cover (land cover change)	Reporting at national level
	Land productivity (net primary productivity, NPP)	
	Carbon stocks (soil organic carbon, SOC)	
UN Framework Convention on Climate Change	Land use change	Reporting at national level
	Carbon stocks (soil organic carbon, SOC)	
UN Sustainable Development Goals SDG 2	Fertility for biomass production (possible indicators are: pH, nutrient content, Organic carbon (OC), cycling of nutrients, water content, soil texture, bulk density)	Reporting at national level
SDG 3	Presence of hazardous contaminants (e.g. trace elements, persistent organic pollutants (POPs), texture, OC))	
SDG 6	Hydraulic properties (e.g. bulk density, texture, OC)	
SDG 13	Organic carbon content (e.g. OC, bulk density, coarse fragments)	
SDG 15	Land degradation indicators[1] and soil biodiversity indicators	
FAO-ITPS 2020 Protocol for the assessment of Sustainable Soil Management	Soil productivity (not a soil indicator, based on yield) Soil organic carbon (%) Soil physical properties (bulk density) Soil biological activity (soil respiration) Additional indicators may be added (e.g. soil nutrients, soil erosion, soil salinity, soil biodiversity, soil salinity, soil pollution)	Reporting mainly at field scale to compare management options
Recommendations of the EU Mission "Soil Health and food"	Presence of soil pollutants, excess nutrients and salts Vegetation cover Soil organic carbon Soil structure including bulk density and the absence of soil sealing and erosion Soil biodiversity Soil nutrients and pH Landscape heterogeneity (linked to soil biodiversity[2]) Area of forest and other wooded lands (not a soil indicator)	Reporting at national level
European Green Deal* From Farm to Fork Biodiversity strategy European climate law Zero Pollution Action Plan (for Air, Water and Soil)	Soil organic carbon stock (i.e. OC, bulk density) Soil biodiversity indicators Soil organic carbon (e.g. OC, bulk density) Concentration of hazardous contaminants (e.g. trace elements, POPs, texture, OC)	Reporting at national level
New CAP	Soil organic matter in arable land Soil erosion by water	Reporting at national level

** To monitor progress for all policies, the implementation of the EU SO is needed.*

5.4 Current national regulations within EJP SOIL countries

The first stocktake among EJP SOIL Partners during 2020 indicated that not all countries have developed and use the same indicators in support to their policies (Annex III in Pavlů *et al.* 2021, summarized in Table 8). The main policy drivers identified were:

- Nitrate regulation, mainly dedicated to water protection but that implies the measurement of nitrogen and phosphorus status in soils
- Contaminated land, sewage sludge and sediment regulations that imply the measurement of trace elements, radionucleotides and organic compounds in past industrial/urban soils and agricultural soils
- UN-FCCC reporting that requires the measurement of carbon stocks variations across time.

Generally, few countries have developed direct policies (e.g. soil protection act or national soil policy) dedicated to soil protection that includes land take, erosion, compaction or biodiversity indicators.

Table 8. Summary of broad parameters implemented in EJP SOIL countries (based on Annex III in Pavlů et al. 2021).

Indicator	No. of countries
Carbon (organic matter)	14
Contaminants	14
Nutrients	14
pH	10
Soil structure[a]	10
Soil biodiversity[b]	3
Gas emissions	2
Soil moisture incl. infiltration capacity	2
Cation exchange capacity	1
Bulk density incl. penetrometric resistance	1

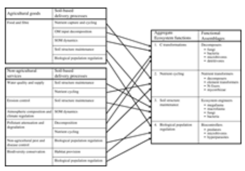
[a] *includes measures of soil structure, texture, stoniness, soil type and soil depth.*
[b] *Most countries specified certain organism groups; earthworms, microarthropods or N_2 fixing bacteria.*

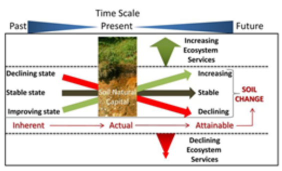
From this summary, it is evident that quite a lot of countries already have implemented soil organic carbon/soil organic matter in their national monitoring schemes, which complies with international policy requirements as described in the previous section. However, there is a wide variation in how many parameters are assessed, where just a few countries are at the forefront including both chemical, physical as well as biological parameters. Much effort would be needed to harmonize assessment of indicators across Europe, if a detailed level of agreement should be intended.

5.5 Review of scientific literature

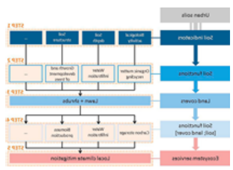
5.5.1 Conceptual frameworks

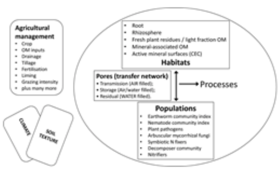
From the 508 publications retrieved in the WoS with the literature search, we selected seven articles that contain conceptual frameworks linking explicitly soil quality or soil quality indicators and ES:

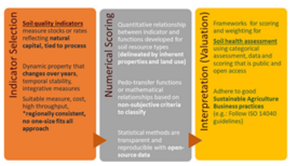

Kibblewhite et al. 2008

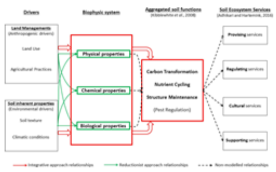

Robinson et al. 2012


Salomé et al. 2016


Blanchart et al. 2018


Stockdale et al 2018

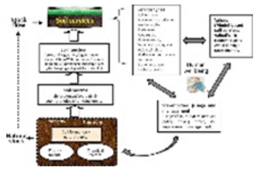

Wander et al. 2019


Thoumazeau et al. 2019

In addition, we manually included three more relevant articles not indexed via our search query:

Pavan and Ometto 2018

Lal 2016



Su et al. 2018

Hence, our analysis considered a total of ten articles that describe conceptual linkage between soil quality and ES.

Of the 508 publications retrieved, the five most productive countries (USA, The Netherlands, Italy, France, and Germany) contributed 72% of the articles (Figure 23). The number of articles published by EU countries (The Netherlands, Italy, France, Germany, Spain, Sweden, Portugal, Austria, Belgium, and Denmark) was 304 (60%). China came out relatively low with 41 articles (8%).

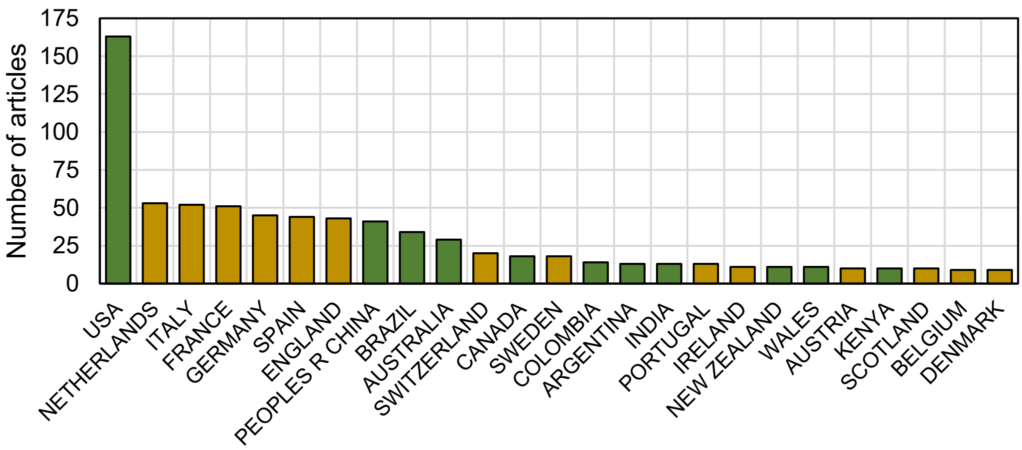


Figure 23. Number of articles on soil quality and ecosystem services by country of origin in 2005-2021. EJP SOIL Member countries in brown.

Although the ES concept is more recent than "soil quality" (Gómez-Baggethun *et al.* 2010, Powlson 2020), the late consideration of research issues linking soil quality indicators and ES assessment remains surprising. Different reasons may explain this: first is that the concept of soil quality has been very ambiguous and heavily criticized in a series of papers (see Bünemann *et al.* 2018). Another reason may be related to the high variability in legislative definitions among countries (again, see Bünemann *et al.* 2018). A further explanation could simply be the lack of a consented, overarching conceptual framework linking soil quality indicators and ES assessment.

A comparison of the selected conceptual frameworks shows that the majority focus on agricultural landscapes and land management, e.g. agricultural management practices (Table 9). The most used concept refers to soil quality, only the framework of Lal 2016 links soil health to soil quality. The majority of frameworks account for soil physical, chemical, or biological 'attributes' or 'indicators'. The consideration of soil contamination indicators such as trace elements or persistent organic pollutants mainly refers to the conceptual framework dedicated to urban soils. In addition to the three last soil attributes, the framework of Lal 2016 also considers soil "ecological" attributes such as erosion, biodiversity, and nutrient cycle. Most of the selected frameworks make distinction between soil processes, soil functions, and soil ES. However, ambiguity remains around the notion of soil processes. For example, soil processes can represent hydrological or geomorphological cycles (Su *et al.* 2018), or can refer to biological activity, available water holding capacity, and saturated hydraulic conductivity (Pavan and Ometto 2018). None of the frameworks discriminate between intermediate and final ES, whereas this is an essential distinction when assessing economical aspects of service provision. Only the framework of Thoumazeau *et al.* (2019) discriminates between manageable and inherent soil properties (*cf.* Dominati *et al.* 2010). Few frameworks consider societal benefits and values of ES, none depict the feedback that can couple with land use and management.

All papers have their advantages and offer various constructive elements, but none answer to all the aspects that we consider elemental features for a framework to bridge the disciplines of ecology and environmental economy, as well as presenting the range of concepts in a consistent context. Thus, a need to further develop an overarching conceptual framework is confirmed. In section 3.1 we have presented a further elaboration of the SIREN conceptual framework based on synthesis of the literature reviewed here, and complemented with feedback from the MS via the Questionnaire, as well as input from discussion with stakeholder institutions.

Table 9. Characteristics of considered conceptual frameworks against key evaluation criteria.

		Thoumazeau *et al.* 2019	**Stockdale *et al.* 2018**	**Blanchart *et al.* 2018**	**Pavan and Ometto 2018**	**Su *et al.* 2018**	**Salomé *et al.* 2016**	**Lal 2016**
Ecosystem type	Agricultural	X	X		X		X	
	Urban			X				
	Other							
	Not specified					X		X
Consideration of land management or cover		yes	yes	yes	yes	yes	yes	unspecified
Concept	Soil Security							
	Soil Health		X					X
	Soil Quality	X		X	X		X	X
	Soil Fertility							
Consideration for:	Soil attributes (or properties/indicators)	X	X	X				X
	Soil processes		X		X	X		
	Soil function	X		X	X	X		
	Soil ES (or ES)	X		X	X	X	X	X
Soil attributes/indicators considered	Physical	X	X	X		X		X
	Chemical	X	X	X		X		X
	Biological	X	X	X				X
	"Ecological"							X
	Contamination			X				
Difference between final and intermediate ES		no		no	no	no	no	no
Difference between soil processes, functions and ES		yes		yes	yes	yes	no	yes
Differentiation between “manageable” and “inherent” soil properties		yes		no	no	no	no	no
Consideration of ES benefits/values		no		no	yes	yes	no	no

5.5.2 SQ and ES indicators

There have been national programs to assess and monitor soil quality through the use of indicators since the end of the 1980s (Bünemann *et al.* 2018). The monitoring in these programs was usually based on analytical approaches, and over the years there has been an advancement in soil quality assessment and monitoring tools. Naturally there is a great variation in the identity of the indicators used in the different programs, and finding suitable indicators to include in SQ and ES monitoring encompass ranking of available indicators based on e.g. ease and cost of sampling and analysis, ease of interpretation, and coupling to important soil functions. Ideally, indicators should be related and/or correlated to soil processes and be responsive to changes in management and environmental conditions (Yang *et al.* 2020).

Several studies indicate the importance of including chemical, physical and biological indicators to assess soil quality (Yang *et al.* 2020; Guerra *et al.* 2021). By measuring soil physics parameters, the aim is to characterize the main aspects of soil systems, including texture, soil aggregates, and bulk density. These in turn relate to the chemical properties of soils (e.g., carbon, nitrogen and phosphorus content) and create an intricate network of soil habitats and specific soil environmental conditions determining, together with soil biodiversity, a plethora of soil functions (including nutrient cycling, soil respiration, litter decomposition, among others) (Guerra *et al.* 2021). However, in actual soil quality assessments there is a preponderance for chemical and physical indicators (Bünemann *et al.* 2018, Valani *et al.* 2020, Figure 24). Overall, total organic matter/carbon and pH are the most frequently proposed soil quality indicators, followed by available phosphorus, and various indicators of water storage and bulk density.

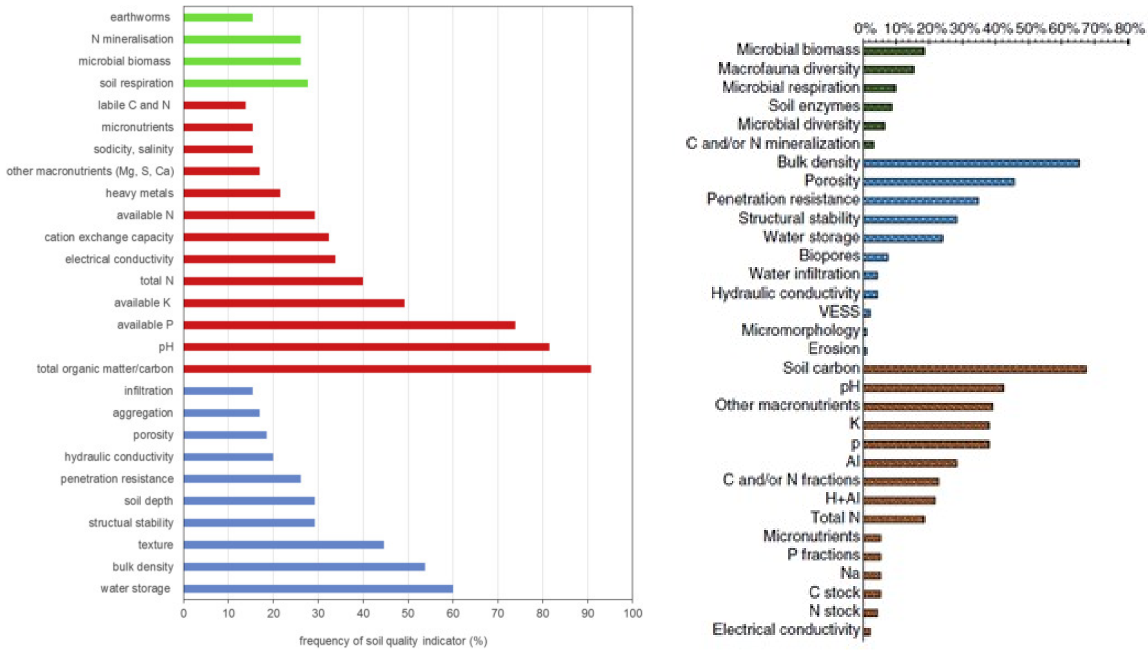


Figure 24. Frequency of different indicators from soil quality assessment approaches (Bünemann et al. 2018), left panel, and assessments of integrated agricultural systems (Valani et al. 2020), right panel.

Soil physical indicators, especially those related to water storage, were frequently proposed in the early assessment schemes and again in the last 5 years, while they were less common in between (Bünemann *et al.* 2018). Among the soil chemical indicators, soil organic carbon content, pH, available P and K, total N, electrical conductivity, cation exchange capacity, and mineral N were proposed more often than all other indicators (Bünemann *et al.* 2018).

Generally, there is a lack of studies involving soil biological indicators, as well as studies assessing soil quality by the integration of soil biological, physical and chemical quality indicators (Valani *et al.* 2020). One difficulty with biological indicators is that they are structured on different spatial scales. For example, parameters contributing to the structuring of microbial communities are (1) on a microscale—the structure, porosity and organic carbon content of the soil; (2) on the scale of a farm plot—the texture, pH, organic matter content, land use and plant cover; and (3) on larger scales (landscape, country)—the physical-chemical properties and land use (Lemanceau *et al.* 2015). Soil respiration, microbial biomass, N mineralization and earthworm density were more frequent among the biological indicators than the other 10 indicators that have been proposed at least once (Bünemann *et al.* 2018).

5.5.3 Mathematical data exploration

Linking data to function

Major challenges in soil modelling arise from the fact that the soil environment is very heterogeneous, that processes occur over a multitude of spatial and temporal scales, and that one has to deal with uncertainties in both models and data (Vereecken *et al.*, 2016). One of the main reasons for using simplified models vs. more complex models for the assessment and quantification of soil processes is the issue of data availability.

Not all soil parameters can be easily assessed. Therefore, soil scientists have developed pedotransfer functions (PTFs) to estimate soil properties from data that are available from soil surveys (Van Looy *et al.* 2017). These mathematical functions relate simple to measure soil properties included in the surveys to less available soil parameters that are not included (Figure 25). However, the PTFs are created for a specific system and might not be directly transferable to a different one. To be able to transfer data from one research project to the next, it is important to validate and harmonize technologies and methodologies as well as standardizing information to achieve sound science that allows reliable translation into relevant information for stakeholders (Keestra *et al.* 2016). These derived soil parameters, together with the directly measured soil parameters are used to assess soil functions (Figure 25).

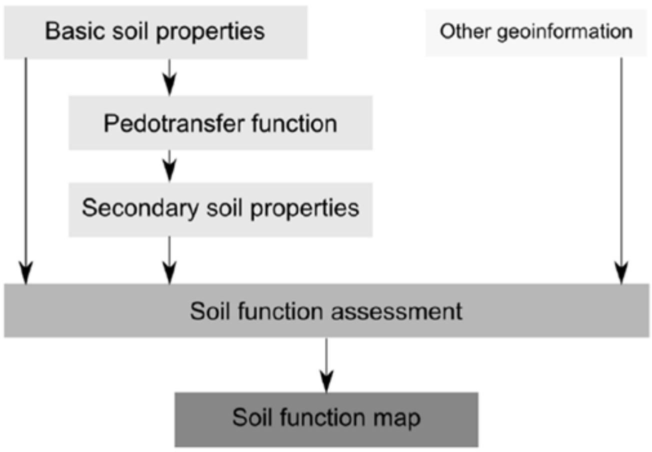


Figure 25. The soil function assessment workflow (Greiner et al. 2017).

There is a range of soil function assessment methods that can be used in ES assessments to create maps of the soil-based supply of ES (Greiner *et al.* 2017). The minimal basic soil dataset required to meet the data demands of a static soil function assessment method is relatively small. The basic soil properties required are the soil organic carbon content, texture (clay and silt contents), pH, stone content, bulk density (or pore volume), and soil hydromorphic properties (e.g., indications on stagnant soil horizons, drainage and water logging data). These soil properties can be regarded as the minimum dataset required to allow at least some basic regulation, habitat, and production sub-functions to be assessed.

The most prominent soil functions assessed in ES studies were contributing to regulation services such as the soil organic carbon pool and the water storage capacity (Greiner *et al.* 2017). The soil C-pool is probably the most often used soil-related indicator because organic carbon in soil is one of the key basic soil properties, is easy to understand, and calculating the soil C-pool is simple and requires only a few soil properties. The plant-available water capacity has been used as a proxy to characterise the soil–water cycle in many studies. Such information is often provided in national soil databases and is often derived from PTFs (Greiner *et al.* 2017). So far, the multi-functionalities of soils have barely been taken into account in ES assessment studies to date, and further efforts to establish applicable methods that link soil biology and soil biodiversity to ES are required (Greiner *et al.* 2017). This implies that although there is a drive for including more soil biological indicators in soil monitoring due to advancement in analysis methods, the lack of methods to further link them to soil functions and ES supply might hamper this development.

Linking soil functions to ecosystem services

The cascade model

The assessment of the flow of ES from nature to society is generally considered a step-wise process, i.e. a cascade model (Figure 26), where the condition describes the overall quality of an ecosystem in terms of its main characteristics underpinning its capacity to generate ES, the capacity describes the ability of a given ecosystem to generate a specific ecosystem service in a sustainable way, the actual use is the amount of an ES that is actually mobilized in a specific area and time, and the benefits are the positive changes in wellbeing from the fulfilment of individual or societal needs and wants (Czucz *et al.* 2020; the theory and terminology date back to Haines-Young and Potschin, 2010 and Hein *et al.* 2016).

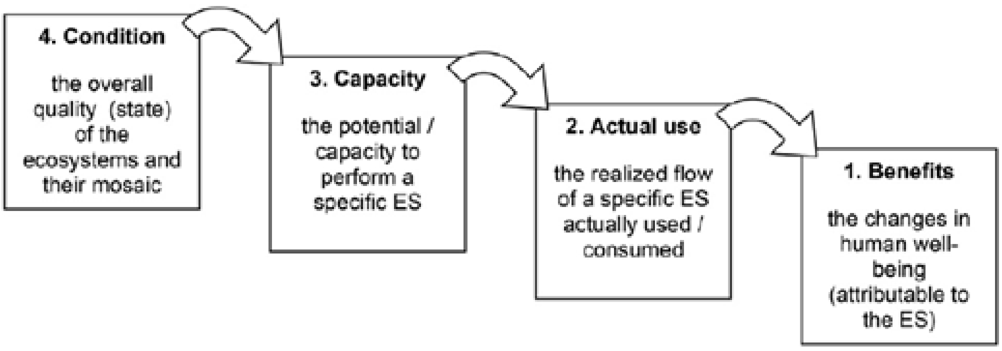


Figure 26. The cascade model (Czucz et al. 2020).

Concepts linking functions to services

ES are derived from soils and landscapes (leaving aquatic and marine environments out of scope here), and the spatial units producing those ES are termed service production areas (Fisher *et al.* 2009) or service-providing areas (Syrbe and Walz 2012). The chemical, physical and biological entities in those soils and landscapes are called service-providing units (SPUs, *sensu* Luck *et al.* 2003), and are the ecological components important in delivering the ES within the service-providing areas: chemical and physical entities with respect to abiotic ES, and biological entities regarding the biotic ES (CICES 5.1). SPUs have a qualitative dimension, i.e. particular species or functional group(s) of species, or processes, as well as a quantitative dimension, i.e. what density, abundance or process rate is required to provide the service at the level required (by the stakeholder) (Luck *et al.*, 2009; Kontogianni *et al.*, 2010). Ecological production functions (EPFs) then can mathematically relate the biophysical structure and ecological processes of ecosystems to the ecological outputs (*cf.* ecosystem function *sensu* de Groot *et al.*, 2002) that drive ES delivery (Munns *et al.*, 2015), and can therefore be used to characterize the relationships between ecosystem condition, management practices and ES delivery (Heal, 2000; Naidoo and Ricketts, 2006).

EPFs can take on different shapes ranging from a simple statistical association between measurement endpoint (e.g. SPU structure or function indicator) and ES provision, to a more mechanistic basis (Bruins *et al.* 2017, Faber *et al.* 2021). Although our understanding of the relationship between land use, biodiversity and service provision is limited (Nicholson *et al.*, 2009), some patterns are emerging. For example, a recent systematic review of 13 ES produced a typology of links between ES and natural capital (Smith *et al.*, 2017), identifying five pathways: amount of vegetation (related to air, soil and water regulation); provision of supporting habitat (related to pollination, pest regulation); presence of particular species, functional groups or traits (related to provisioning ES, species-based cultural services); biological and physical diversity (related to landscape-based cultural services); abiotic factors (related to water supply).

The approach of application of EPFs to assess ES provision has been worked out for environmental risk assessment for chemicals (Faber *et al.* 2021), and this may serve as a more detailed example of stepwise modelling of ES provision and further economic valuation. Here data from standardised toxicity testing using "standard" test species is conceptually used to assess the impact of chemicals on the functioning of service providing taxa to consequently assess impact on service provision using EPFs (Figure 27). The Faber *et al.* (2021) paper reviewed literature to compile quantitative information on ES provision by ecological receptors susceptible to environmental stressors, in particular chemicals, and may be seen as an example approach to using raw environmental data in successive quantitative extrapolation steps to assess environmental health and associated economic values. The catch is of course the availability of applicable relationships, and the paper exemplary - not exhaustively- reviews these for all biotic ES in the CICES V5.1 catalogue to illustrate the feasibility of this approach.

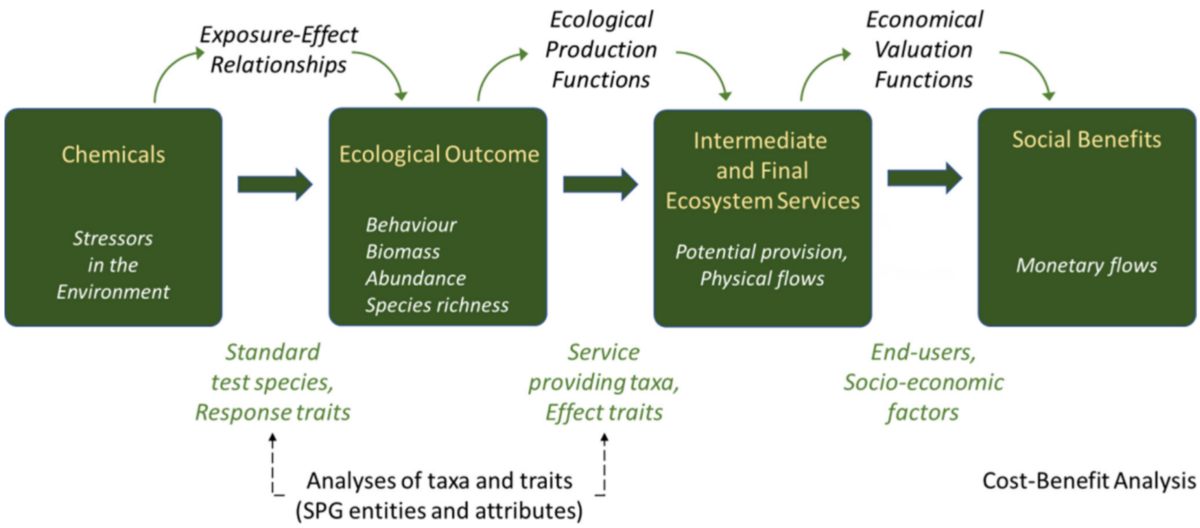


Figure 27. The translation of effect data from standardised ecotoxicological testing for ES impact assessment using ecotoxicological exposure-effect relationships and ecological production functions based on response traits and functional traits (also called 'effect traits') respectively. EPFs quantify potential provision of intermediate or final services, and socio-economic factors determine actual flows of services 'physical flows' and benefits 'monetary flows'.

ES assessment models

There are two noteworthy models including multiple ES – also soil-based ES – that are increasingly used in ES assessment studies: The Integrated Valuation of Ecosystem Services and Trade-offs model (InVEST) and the Artificial Intelligence for Ecosystem Services model (ARIES) (Greiner *et al.* 2017). The InVest model is a suite of software models based on production functions that define how an ecosystem's structure and function affect the flows and values of ES. The toolset currently includes seventeen distinct models suited to terrestrial, freshwater, and marine ecosystems (Prado *et al.* 2016). On the other hand, ARIES is an integrated ES modelling methodology and web application which allows assembly of customized models from a growing model base. In addition to these two models, there is a range of other tools to model and assess ES (Prado *et al.* 2016).

Four key challenges in modelling soil processes that are directly related to the hierarchical and complex organization of soils and soil systems and the functioning of soils in providing ES to society challenges has been identified (Vereecken *et al.* 2016):

1. To effectively exchange soil processes modelling and knowledge across different soil disciplines, and with Earth, ecology, and plant sciences
2. To build platforms for integrating soil processes from pore and local scales into field and ultimately global-scale land surface models, crop models, climate models, and terrestrial models of biogeochemical processes
3. To improve quantification and mechanistic representation of soil biological processes at scales ranging from microbial cells at pores or on root surfaces to the emergence of vegetation patterns over extensive landscapes
4. To develop a framework that allows to differentiate soils based on their functioning properties and include land use and/or tracking changes of supporting–degrading processes toward building spatial maps that quantifying ES and may contribute to improve the valuation of ES.

Solving these challenges would greatly benefit the inclusion of assessment of ES in monitoring schemes.

5.5.4 References, thresholds and target values

The increase in agricultural production through intensification and land use conversion has in many cases led to the maximization of one ecosystem service (production of food, fodder or fibre) at the expense of other services (Figure 28). On the other hand, appropriate management can optimise the supply of multiple ES, while biodiversity-friendly agricultural practices make an important contribution to achieving EU conservation targets. The setting of targets and thresholds to SQIs in view of ES provision should include all relevant soil-derived services, and not just the single most-important service (which in the case of agriculture is crop production). Clearly, this is to facilitate the trade-offs and synergies between bundles of ES, in order to evaluate SQ in a context of sustainability objectives that policy has set out.

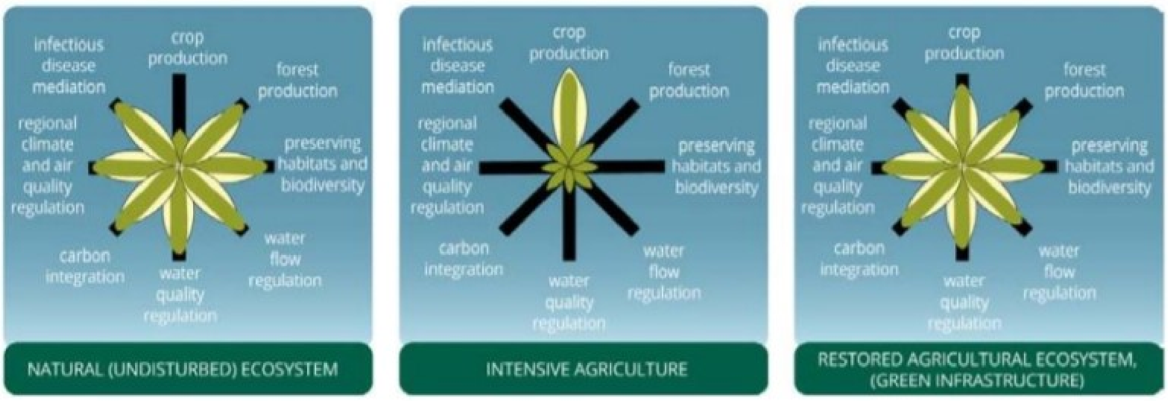


Figure 28. Capacity of cropland ecosystems to provide services under natural conditions, intensive and balanced management showing trade-offs of ES. The provisioning of multiple ES under different land-use regimes can be illustrated with these simple "flower" diagrams, in which the condition of each ecosystem service is indicated along each axis. Axes can be expressed in comparison to a reference, or normalized with common units, but in this qualitative illustration the axes are not labelled (Source: EC 2017; adapted from Foley et al. 2005).

References

For agroecosystems, agreement by multiple actors about the definition of "good condition" is available for natural or semi-natural grasslands when covered by the nature legislation (Annex I habitats of Habitats Directive), but very little exists for cropland which could serve as a starting point for the discussion regarding terrestrial ecosystems, and soils in particular (in contrast to freshwater

ecosystems for which the definition of good environmental status in the Water Framework Directive can be applied).
Based on the policy and scientific targets set out above, the condition of agroecosystems can be defined as follows (EC *et al.* 2017):

> *Agroecosystems are modified ecosystems, they are in good condition when they support biodiversity, abiotic resources (soil-water-air) are not depleted, and they provide a balanced supply of ES (provisioning, regulating, cultural). Sustainable management is key to reaching or maintaining a good condition, with the aim to increase resilience and maintain the capacity of delivering services to current and future generations.*

This sets the policy-defined contours for further scientific elaboration of target values for SQIs. One of the main scientific challenges here is a major lack of knowledge on trade-offs, where the state of the art is at an observational level of quantification, rather than of predictive modelling.
Also, the level of definition of references may be higher than the soil parameters themselves, since the criterion is expressed in view of the provision of ES. In the former Dutch approach [14]to setting references for biological soil quality (Rutgers *et al.* 2008), scientists' expert knowledge was used to assign the best sites from a monitoring database on a particular combination of land use and soil type, assessing measurements for 23 different parameters, and the averaged parameter values were benchmarked, together making up the reference for that particular land use-soil type combination (Figure 29). This approach may be applied to specific farms to assess local soil quality in a comparison to the reference for these farms, given soil type and land use (Figure 30).

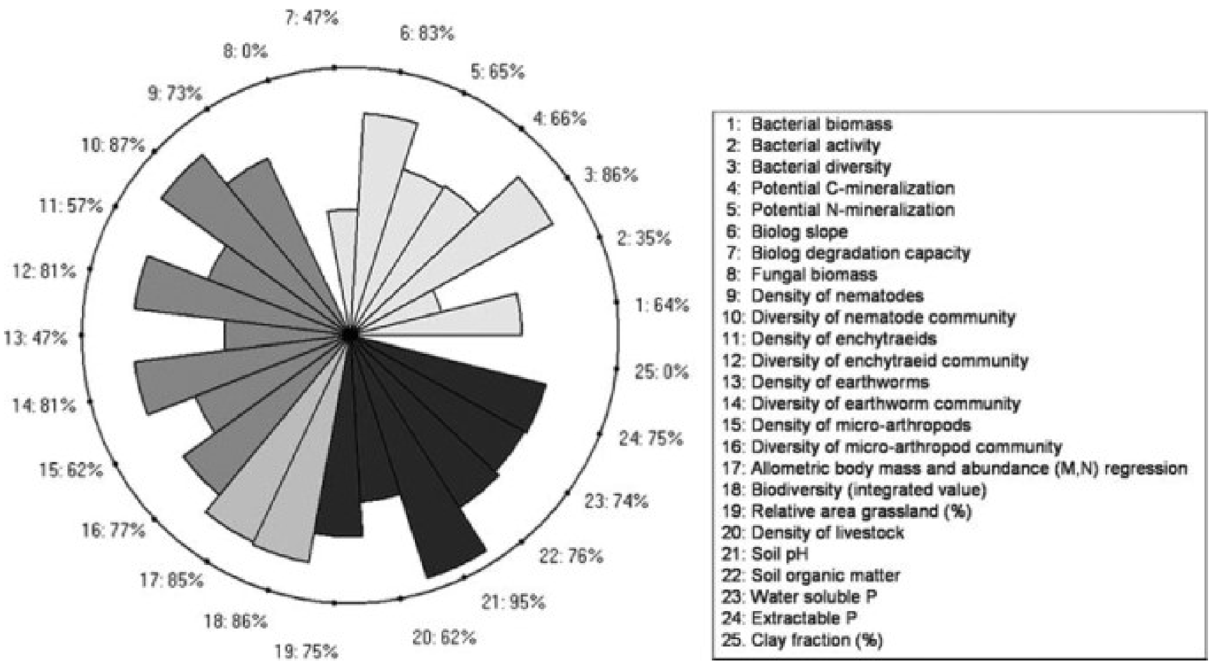


Figure 29. Amoeba diagram illustrating the reference biological soil quality for dairy farm grasslands on sandy soils in the Netherlands, consisting of 25 soil parameters. The circle represents the 100% benchmark for an expert judgement estimated healthy soil, as an average of six locations representing "good quality" from a total of 81 locations monitored. Pie segments represent the average deviation from the benchmark, starting with the microbial parameters (lightest grey) at 3 o'clock and turning anti-clockwise to end with the soil quality management data and chemical and physical parameters (darkest grey) (Rutgers et al. 2009; actual values provided in Rutgers et al. 2008).

[14] The project 'Biological Indicator for Soil Quality' has been discontinued since 2014.

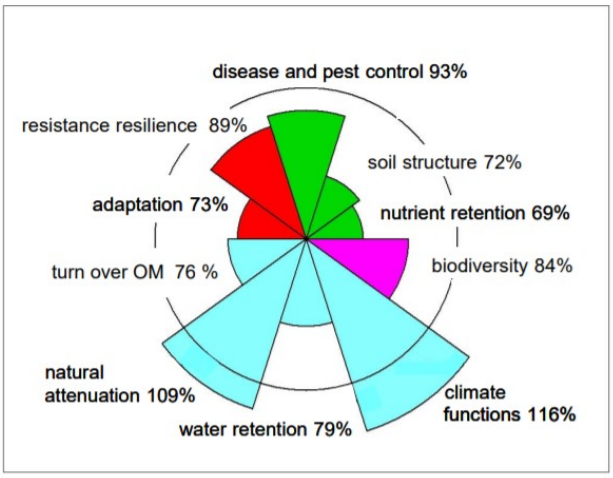


Figure 30. Amoeba chart showing the average performance of 10 ecosystem services for four farms in the Hoeksche Waard polder area (West Netherlands), compared with the national benchmark value for arable farmland on clay (100% circle) (Rutgers et al. 2008). The ecosystem services are aggregated in four main groups indicated by colours. The nutrient supply service, for example, has a score of just below 70% relative to the sustainable reference. On the other hand, the soil's climate function and natural attenuation are better on these farms than in the national reference.

In a related study it was shown that differences in ecosystem service performance between four neighbouring farms with similar rotation system were probably related to the specific land management, such as tillage, manure and pesticides use (Rutgers *et al.* 2007).

More recently, developments anew have led to an alternative system of soil quality indicators, 'Soil indicators for agricultural fields in the Netherlands' (BLN) (i.e. for agricultural soils only), which currently includes a selection of 18 important indicators to give a reliable representation of integral soil quality (Hanegraaf *et al.* 2019, De Haan *et al.* 2021). This includes classical, reliable, but sometimes expensive and slow measuring methods, as well as alternative, quick and cheaper methods. The BLN in its current version can be used for all combinations of soil types and agricultural land use in the Netherlands, and for four combinations, target values or reference values are provided.

Another way to develop reference values or normal operating ranges is to have access to large datasets. Using a dataset of soil molecular microbial biomass and bacterial diversity in soils together with pedoclimatic properties derived from analyses of samples collected in the context of the French monitoring soil quality network "Réseau de Mesures de la Qualité des Sols" (RMQS), Terrat *et al.* (2017) and Horrigue *et al.* (2016) developed models to explain and predict biological endpoints depending on land use, organic carbon content, clay content, altitude and pH. Such models may then be used to diagnose soil status based on soil "classical parameters" and additional information such as land use and altitude.

References for SQIs

How to establish evaluation criteria for indicators for soil quality, particularly reference values and thresholds, that comply to the context of sustainable development?
Firstly, reference values for indicators soil health should express soil functions, because soil functions are the linkage from processes by the soil systems to the valuation of performance or their services in the context of sustainable development. This follows from the definition of soil health. Secondly, criteria should reflect the relationship between soil functions and land use and soil management. To assess the interaction between soil management and soil functions, there is a need to identify soil functional characteristics that integrate systemic knowledge about the complex, non-linear interactions between soil components and processes on various temporal and spatial scales on the

one hand, and to link them to soil management practices, especially combinations of practices, on the other hand.

The functional characteristics of soils result from the interactions between soil structural components (e.g., minerals and particles, plant roots, and soil organisms) and physical, chemical and biological processes in soils. They are affected by soil management and may change at a time scale of days to months. Examples of functional characteristics are organic matter build-up and breakdown, water infiltration capacity, aggregate stability, macropores, and functional group diversity. Reference values for such functional characteristics, i.e. their typical range, will depend on the soil type and the inherent soil properties that are stable at a time scale of at least decades. They in turn influence state variables (e.g., water content, biological activity and temperature) that can change very quickly within days. The challenge is an in-depth exploration of the spatial and temporal dynamics of soil functional characteristics as the basis to derive meaningful indicators for soil functions that are sensitive to the key pressure of (agricultural) soil management (Bünemann *et al.* 2018).

5.6 European research projects

ENVASSO

Several EU research projects have proposed sets of indicators to assess soil threats, one of these being the EU-FP6 project ENVASSO (ENVironmental ASsessment of Soil for mOnitoring). The project's main objective was to define and document a soil monitoring system for implementation in support of a European Soil Framework Directive, aimed at protecting soils in the EU. The ENVASSO consortium reviewed currently available soil indicators and criteria (Huber et al, 2008), and existing soil inventories and monitoring programmes in the MS (Arrouays *et al.* 2008a, 2008b). A database system to capture, store and supply soil profile data was designed and programmed (Baritz *et al.* 2008), and procedures and protocols were defined and fully documented (Jones *et al.* 2008). Several of these procedures were also evaluated in pilot studies (Micheli *et al.* 2008, Stephens *et al.* 2008), and a design for a European Soil Monitoring System was described (Kibblewhite *et al.* 2008). Regarding soil indicators, ENVASSO identified three priority indicators for nine different soil threats identified by the European Commission (Huber *et al.* 2008). The main focus was on state, pressure and impact indicators, and the main criteria for selection were indicator significance, methodological soundness, measurability and policy relevance. Some of the selected indicators are chemical, physical and biological SQ indicators such as soil organic carbon and carbon stock, concentration of heavy metals, sulphur and nitrogen, electrical conductivity, bulk density, diversity of earthworms and collembolans, and microbial respiration.

RECARE

The priority indicators identified within the ENVASSO project were further revised and amended by the EU-FP7 project RECARE (Preventing and Remediating Degradation of Soils in Europe through Land Care) (Table 10), The aims of the RECARE project of relevance for SIREN were to fill knowledge gaps in our understanding of the functioning of soil systems under the influence of climate and human activities, to develop a harmonised methodology to assess the state of soil degradation and conservation, and to develop a universally applicable methodology to assess the impacts of soil degradation upon soil functions and ES. Two needs or difficulties of relevance for SIREN were highlighted by the project; lack of harmonization on which methods/models to use over which spatial and temporal scales, and lack of a method to provide an overall measure of soil biological health (Stolte *et al.* 2016). Instead, as already established in ENVASSO a suite of soil biological methods was suggested to provide an informative approach and incorporate both soil biodiversity and soil function. Part of the indicators suggested by ENVASSO and RECARE were discussed and included in the recent report from EEA (Baritz *et al.* in prep.).

Table 10. Comparison of defined soil threat indicators within the European research projects ENVASSO and RECARE. The table was extracted from the iSQAPER website, and modified after Stolte et al. (2016).

Soil threat	ENVASSO (Huber *et al.* 2008)	RECARE (Stolte *et al.* 2016)
Soil erosion	Estimated soil loss by water erosion (rill, inter-rill, and sheet erosion)	Area affected by soil erosion (km^2); magnitude of soil erosion/deposition or sediment delivery (tons)
	Estimated soil loss by wind erosion	Measured soil loss by wind ($t\ ha^{-1}\ yr^{-1}$); estimates of wind erosion; susceptibility to wind erosion; various proxy indicators
	Estimated soil loss by tillage erosion	Not specified
Decline in soil organic matter	Topsoil organic carbon content (measured)	Clay/SOC; topsoil organic carbon content
	Soil organic carbon stocks (measured)	Total carbon stocks to 1 m depth
	Peat stocks (calculated or measured)	Peat stocks
Soil contamination	Heavy metal contents in soils	
	Critical load exceedance by sulphur and nitrogen	
	Progress in management of contaminated sites	
Soil sealing	Sealed area	Sealed area
	Land take (Corine Land Cover)	Transition index (TI)
	New settlement area established on previously developed land	Sealed to green areas ratio
Soil compaction	Density (bulk density, packing density, total porosity)	Relative normalized density
	Air-filled pore volume at specified suction	Air-filled pore volume
	Vulnerability to compaction (estimated)	Penetration resistance
Soil biodiversity loss	Earthworms diversity and fresh biomass	
	Collembola diversity (enchytraeids diversity if no earthworms)	
	Microbial respiration	
Soil salinization	Salt profile (total salt content or electrical conductivity)	
	Exchangeable sodium percentage	
	Potential salt sources (groundwater or irrigation water) and vulnerability of soils to salinization/sodification	
Landslides	Occurrence of landslide activity	
	Volume/weight of displaced material	
	Landslide hazard assessment	
Flooding	Not addressed	Seasonality, magnitude, frequency of precipitation/rainfall intensity; extent of inundated area; flood frequency; loss of crops due to inundation of fields
Desertification	Land area at risk of desertification	
	Land area burnt by wildfires	
	Soil organic carbon content in desertified land	

LANDMARK

A more recent research project is the H2020 LANDMARK (Land Management Assessment, Research, Knowledge base) project, which aimed at quantifying 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. The objectives were to produce 1) a 'Soil

Navigator' that provides advice on the sustainable management of soils for farmers and advisors, 2) a framework for monitoring of soil quality and soil functions that is applicable across Europe for legislators, and 3) an assessment of policies that can ensure that we 'make the most of our land', from both an agronomic and environmental point of view, for policy makers. In comparison with the above reviewed projects, the focus of LANDMARK was soil functions rather than soil threats. LANDMARK has proposed indicators to assess five main soil functions: primary productivity, water purification and regulation, climate regulation and carbon sequestration, soil biodiversity and habitat provisioning, and provision and cycling of nutrients. Each soil function includes decision models and input data, and all decision models developed have a similar hierarchical structure (number of hierarchical levels), as well as the same number of basic attributes. The decision models for all five soil functions use the same subset of basic attributes, so the total number of distinctive input attributes for all decision models is 75.

The primary productivity decision model consists of sub-models describing the environmental conditions (E), inherent soil conditions (S) (physical: structure, groundwater table depth; chemical: micro- and macro-elements; biological: pH, C/N ratio, soil organic matter), soil management (M), and crop properties (C). Primary productivity, as the top attribute, integrates the sub-models, which leads to an assessment of the capacity of a soil to produce biomass. A detailed description of the primary productivity model is given in Sandén *et al.* (2019).

The structure of *the nutrient cycling decision model* consists of three sub-models, integrated into the top attribute, describing the ability of a soil to provide and cycle nutrients. The first sub-model comprises nutrient fertilizer replacement value, which describes the extent to which nutrients, particularly those in left or applied organic residues, are as available to plants as manufactured mineral fertilizers. The second part of the model describes the extent to which plant-available nutrients are effectively taken up by crops and the last part addresses the harvest index describing the extent to which the nutrients taken up by crops are eventually leaving the field in the form of successful harvests (Schröder *et al.* 2018).

The climate regulation and carbon sequestration decision model integrates carbon sequestration, N_2O emissions and CH_4 emissions. The carbon sequestration sub-model is determined by the magnitude of carbon inputs, carbon losses, and the soil organic carbon concentration. The N_2O emissions sub-model makes a distinction between direct N_2O emissions occurring on agricultural fields, and indirect N_2O emissions, after reactive N species have been transported through the landscape. The part of the model addressing CH_4 emissions are determined by the extent to which artificial drainage is applied on organic soils. Detailed information about the model is given in Van de Broek *et al.* (2019).

The water regulation and purification soil function decision model integrates three sub-models describing the prevailing soil water pathways: water storage, water runoff, and water percolation. Water storage is determined by the attributes used for assessing the water holding capacity and soil moisture deficit. Water runoff is determined by the attributes used for assessing the water-, sediment-, and nutrient-related runoff. The water percolation sub-model is determined by the attributes used for assessing the resulting drainage of excess of water above that potentially stored in the soil and the resulting nutrient leaching and losses (Wall *et al.*, 2020).

The soil biodiversity and habitat provisioning decision model integrates four sub-models describing soil nutrients (status, trends, turnover, and nutrients availability), soil biology (available information on diversity, biomass, and activity of soil organisms), soil structure [structure and density, ranging from mesoscale (coarse fractions, soil particles, organic matter, air, and water-filled space) to macroscale (soil layers, terrain, slope)], and soil hydrology (soil humidity and the soil water flow pathways) (van Leeuwen *et al.* 2019).

These decision models highlight the amount of input data, in the form of chemical, physical and biological indicators, that is needed to better assess vital functions provided by soils. These decision models have then been combined into a decision support system, named the Soil Navigator, which provides an integrated assessment of the five soil functions and allows an assessment of trade-offs between soil functions for a specific agricultural management practice (Debeljak *et al.* 2019).

5.7 National Ecosystem Assessments

Astrid Taylor and Jack Faber

Information from soil and ES assessments, such as ES maps, has been given priority for spatial planning and decision making by government and non-governmental organizations (e.g., Egoh *et al.* 2008, Maes *et al.* 2012). The European Biodiversity Strategy to 2020 recognized ES mapping as a strategic action and EU Member States were stimulated to map and assess the state of ecosystems and their services (Hauck *et al.* 2013, European Commission 2011).

We performed a review of national ecosystem assessments (NEAs) to analyse if soil data were used, what kind of indicators were used, and how these data were used to quantify the related ES. We selected NEAs from eleven countries that differed considerably in their objectives, methods and suggested operationalisation of concepts, enumerated in

Table 11. The range spans from (nearly) completed NEAs [Portugal (2009), UK (2011), Spain (2012, 2014), Flanders (2014)] to scoping studies or stock takings at different stages of development [Norway (2013), Netherlands (2014, 2020), Finland (2015), Germany (2015, 2017), France (2012-2018), Estonia (2016-2020), Slovakia (2020), and a first draft of an agenda for the implementation of a national ES assessment (Greece 2017).

The British, Finnish, German, Greek, and Slovakian NEA reports were available in English. For some of the remaining NEAs, key findings or a synthesis were available in English as well: Regional EA Flanders - 'Key findings of the technical report' (Stevens *et al.* 2015); Portuguese EA - 'Executive summary of the final report' (2009); Spanish NEA - 'Synthesis of Key findings' (2014); French NEA – 'Key messages for decision makers (2018)' (available for all six assessed ecosystems). We did not find English texts for the Norwegian, Dutch and Estonian NEAs (

Table 11).

From this review of NEAs some general observations can be made. First, the reports generally described ES in relation to service providing entities in the ecosystem, such as the key organisms contributing to ecosystem functioning in the provision of a particular service. While this is suggesting what the assessment was based on, it often remained unclear whether actual soil data parameters had been used, and what measurement method had been used. It was therefore unclear which specific SQIs were involved, if at all. The UK study can be seen as an example by exception, were various supporting, provisioning and regulating services have been assessed using soil data from the 'Countryside Survey' (Emmett *et al.* 2010), as well as from more local studies. The soil indicators used in this assessment are summarised in

Table 12. A methodological drawback in this comprehensive approach, however, has been the combination of data from different years and spatial areas: soil monitoring and ecosystem assessments have not been synchronised in time and space.

Table 11. Overview of NEAs selected for review, ordered by year of publication.

Country	Reference	Short description	Language
Portugal	Pereira *et al.* (2009)	One of the sub global assessments conducted as part of the Millennium Ecosystem Assessment. It assessed nine ecosystem types and a selection of ES, and it contained five case studies.*	Portuguese with English synthesis
United Kingdom	UK NEA (2011)	Most comprehensive NEA in Europe, assessing eight ecosystem types and a large number of related ES. It contained four regional assessments on the status and trends of ecosystems and ES, as well as an exploration of different forms of the valuation of ES.*	English
Spain	EME (2012) EME (2014)	EME 2012 assessed 14 ecosystem types (including terrestrial, aquatic, transition, and urban ecosystems) and 22 ES, including five case studies. The 2014 report is on economic valuation (EME 2014).*	Spanish with English synthesis
Norway	NOU (2013)	Expert report for the Norwegian national parliament that assessed 11 ecosystem types, as well as a biophysical and monetary valuation of a selection of ES.*	Norwegian
Belgium (Flanders)	INBO (2014)	Subnational ecosystem assessment that focused on spatially quantifying 16 ES and the state and trends of biodiversity, as well as its role in the provision of ES.*	Dutch with English synthesis
Netherlands	de Knegt (2014) de Knegt *et al.* (2020)	Quantification of the state and trends of the provision and the actual use of 17 ES in the Netherlands.* Update in 2020	Dutch
Finland	Jäppinen and Heliölä (2015)	TEEB report that contained a short assessment of 28 ES and case studies on mapping the value of ES.*	English
Germany	Albert *et al.* (2015, 2017)	Scoping study that recommends national ES indicators and provided maps on the current state of these indicators.* Follow up initiative in 2017 focused on how to proceed towards an implementation in Germany.	German and English
France	EFESE (2020)	(1st phase 2012–2018) Program and science-policy-society platform led by the Ministry for an Ecological and solidarity transition. A first phase of the program (2012–2018) took stock of the state of six French ecosystems.	French, English key messages for decision makers
Greece	Dimopoulos *et al.* 2017	First outcomes of the Hellenic Ecosystem Services Partnership (HESP), a scientific-technical committee aiming at the guidance and coordination of the Ecosystem Services (ES) assessment in Greece.	English
Slovakia	Mederly *et al.* 2020	Pilot national ecosystem services assessment in Slovakia with selection of 18 significant ES.	English
Estonia	Oja *et al.* 2020	Project *ELME* by the Estonian Environmental Agency for a nationwide evaluation and mapping of ecosystems and their services (four ecosystems: meadow, swamp, forest, agricultural ecosystems).	Estonian

*From Schröter *et al*. (2016)

Second, it could also not be reconstructed from any of the NEA reports by how the soil data had been extrapolated to quantify the ES. It appears that the assessments using soil data stop at the level of soil functions, and were not extrapolated to any spatial aggregation, let alone that socio-economic evaluations were made to quantify the flow of services towards relevant stakeholders with consequent valuation of costs and benefits.

Third, the studies were generally focused on a limited number of ES and because of that were also generally limited in their potential to assess trade-offs between bundles of ES. Considering the current view on soil health (Giuffré *et al.* 2021), future ecosystem assessments should be designed to facilitate this aspect of assessment.

Table 12. Summary of soil indicator data used in UK Ecosystem Assessment.

Ecosystem Service Section		Soil Indicator	Reference cited in the UK NEA
Supporting services	Soil formation	Stock estimates: total mass of soil, carbon, nitrogen, phosphorus [Mt] based on depth of soil to the parent material and bulk density	Smith *et al.* (2007)
		Stock of soil carbon in relation to depth (surface and deeper soil horizons)	Bellamy *et al.* (2005), Countryside survey (2010)
		Rate of organic matter accumulation or loss	
		Rate of carbon fixation/accumulation [t C/ha/yr]	
		Plant functional diversity (i.e. the range, type and relative abundance of plant functional traits)	
	Nutrient cycling	*Nitrogen* 1) Nitrogen mineralisation a) Nitrogen stock: stock of total mineralisable nitrogen [kg N/ha] b) Nitrogen availability: mineralisable nitrogen concentration in soil organic matter [mg N/kg loss-on-ignition]	Emmett *et al.* (2010)
		2) Topsoil carbon:nitrogen ratios	Emmett *et al.* (2010)
		Phosphorus Extractable Phosphorus (Olsen-P) [mg P/kg soil]	
		Soil acidity pH in rainfall and soil (0–15 cm) using ordinary Kriging (pH units)	
		Trace elements Boron, copper, zinc, sulphur, selenium in soil	
	Water cycling	Volume of water in saturated soil	
	Primary production	Crop yield [tonnes/hectare]	
		Nitrogen deposition	
		Availability of nutrients (especially nitrogen and phosphorus)	
		Rate of carbon accumulation [t C/ha/yr]	
Regulating services	Climate regulation	Soil carbon storage and density (kg per m^2)	
		Nitrous oxide emissions	
		Soil erosion: diff. methods mentioned, rates derived using caesium-137 (137Cs) represent all erosion processes	
		Carbon budgets of peatlands	
	Soil quality regulation *)	*Indicators mentioned in the UK NEA:* Soil carbon (surrogate measure for Soil Organic Matter (SOM) content)	
		Topsoil concentrations of heavy metals (0–15 cm)	
		Soil pH: critical loads of acidity	
		Critical loads for nitrogen (RoTAP 2011)	
		Soil water retention capacity	
		Soil bulk density (e.g. reduced aeration can be detected)	
	Air quality regulation	Soil temperature	
		Soil water availability	
	Water quality regulation	Pollutant sequestration in soil, microbial pollutant uptake	
		Dissolved organic carbon	Monteith *et al.* 2007
		Evapotranspiration from soils	
Provisioning services	Food, fiber and energy from agriculture	Crop yield [tonnes/ hectare]	
		Area of land under crops [ha]	
	Peat	Peat extraction [ha or m^3]	

**) Quoted from UK NEA: "Indicators of soil quality relevant to regulating services have been extensively reviewed (Environment Agency 2006, Aalders et al. 2009, Defra 2009), demonstrating recognised gaps in suitable indicators of physical soil quality (addressing soil structural changes and water transfer) and in the need for soil profile assessments."*

5.8 Stakeholder views

5.8.1 International institutions

JRC

The Joint Research Centre (JRC) is the science and knowledge service of the European Commission, which employs scientists to carry out research in order to provide independent scientific advice and support to EU policy. In 2020, JRC published a report (Panagos *et al.* 2020) on 'Soil related indicators to support agro-environmental policies' that proposed to include the following issues: soil erosion (based on modelling), soil carbon changes and soil nutrients (based on LUCAS database measurements of C, N, P, and K). It also provided baselines for evaluating the current status of agricultural soils in the European Union and evaluating the impact of agri-environmental policies on land management. In addition, a soil fertility index was proposed.

European Environment Agency

The European Environmental Agency (EEA) is an agency of the European Union, with the task to provide sound, independent information on the environment. EEA has developed the following indicators related to soils:

- Soil moisture[15] and soil moisture deficit[16]
- Imperviousness and imperviousness change in Europe[17]
- Land recycling and land use densification[18]
- Progress in management of contaminated sites[19]
- Soil organic carbon[20]

A report is drafted on soil quality indicators in view of soil threats (Baritz *et al.* in prep.). The report aims to synthesize the current knowledge about soil indicators in the context of land degradation, ecosystem condition and soil resource use efficiency, and presents selections of well-defined and standardised indicators that as a set are considered suitable for the assessment of soil threats when applied in structural soil monitoring at national level across EU. Importantly, threshold values were proposed for soil organic carbon (depending on soil texture), nutrients (depending on land use, forest or agriculture), acidification, erosion, compaction and soil sealing.

In a direct discussion with EEA (Rainer Baritz) we noted the following ideas that we consider very relevant to the SIREN objectives:

- Linkage between soil functions and ES needs clarification
- Scientific developments in frameworks and indicators for SQ tend to be too complex for policy implementation; things should be kept simple[21];
- SQ monitoring is driven by purpose, and the selection of adequate indicators should reflect soil function and soil threats; depending on the purpose, different sets of indicators can be used, but few and simple and made practical;
- Screening values should reflect the impact on key parameters associated with soil functions;
- Implementation of SQIs in monitoring can be in steps (EEA: Levels I, II and III), *cf.* as has been established in forest monitoring:
  - I. EU wide, not soil dependent, including LUCAS;

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[15] https://www.eea.europa.eu/data-and-maps/indicators/water-retention-4/assessment
[16] https://www.eea.europa.eu/data-and-maps/indicators/soil-moisture-deficit/assessment
[17] https://www.eea.europa.eu/data-and-maps/indicators/imperviousness-change-2/assessment
[18] https://www.eea.europa.eu/data-and-maps/indicators/land-recycling-and-densification/assessment-1
[19] https://www.eea.europa.eu/data-and-maps/indicators/progress-in-management-of-contaminated-sites-3/assessment
[20] https://www.eea.europa.eu/data-and-maps/indicators/soil-organic-carbon-1/assessment
[21] This is also why the report from EEA mainly focused on indicators for measuring soil threats and not soil functions and/or soil related ecosystem services, as soil threats have been discussed and assessed for years.

- II. Ecosystem related, national scale, more sites and samples (deeper horizons), including soil biota, extended frequency;
- III. Flux monitoring

FAO

The Food and Agriculture Organization (FAO) is a specialized agency of the United Nations that leads international efforts to defeat hunger. In 2012 FAO established the Global Soil Partnership (GSP), as a response to the recognition of the critical role of soils for food security and ES. GSP is an interactive, responsive and voluntary partnership, open to governments, regional organizations, institutions and other stakeholders at various levels. The Intergovernmental Technical Panel on Soils (ITPS) provides GSP with scientific and technical advice on global soil issues. Last year, FAO published their synthesis report on the state of the global land and water resources for food and agriculture, stating that agricultural systems are at "breaking point", and emphasizing the need for accurate information and a major change in resource management as well as the requirement for complementing efforts from outside the natural resources management domain to maximize synergies and manage trade-offs (FAO 2021). As recent as 28 January 2022, at the annual Global Forum for Food and Agriculture meeting, 68 agriculture ministers from around the world reached consensus to protect and use soils sustainably. Their communiqué reiterated the lack of reliable data, specifying that over 55 percent of surveyed Members of the Global Soil Laboratory Network (GLOSOLAN) lack adequate analytical capacities, including human resources, harmonization procedures and equipment (FAO-GFFA 2022). Earlier, in 2020, FAO-ITPS published a protocol for the assessment of sustainable soil management including a recommended set of indicators (FAO-ITPS 2020). These include soil organic carbon, bulk density and soil respiration, and additional indicators for specific cases are also mentioned (more details in Table 7).

IUCN

International Union for Conservation for Conservation of Nature (IUCN) is a membership union composed of both government and civil society organisations. As the global authority on the status of the natural world and the measures needed to safeguard it, the organisation is interested to develop a global evaluation tool for the assessment of biodiversity in agroecosystems. We have spoken with a group of students at the Graduate Institute in Geneva doing a consultancy project advising on the development of a global index for agrobiodiversity. The relationship between biodiversity and provision of ES for agriculture ("functional agrobiodiversity") was discussed, including what service providing biota would be relevant considering soil biodiversity. A global index for agrobiodiversity should allow for regional and continental differences in key functional groups. Importantly, linkage is needed between biodiversity and ecosystem functioning and the delivery of ES, in order to not only evaluate biodiversity status but also its function in supporting the agroecosystem. Linking structure and function is considered a knowledge gap, particularly where in different agroecosystems and other parts of the world the same functions are performed by different taxa. No documents for referencing exist yet at the time of writing our report.

GSBI

The Global Soil Biodiversity Initiative (GSBI) is a volunteer scientific organization with the goals of informing the public, promoting this information into environmental policy, and overall creating a platform for the current and future sustainability of soils. Therefore, it does not have a position on indicators or how they are used or assessed. However, GSBI sponsor working groups to assess and integrate results across disciplines that can be used to identify gaps needed for qualifying and/or quantifying global soil biodiversity and relating it to ecosystem models. It is also vital in aiding the knowledge transfer from science to policy.

In the outcome document of the Global Symposium on Soil Biodiversity (GSOBI21), which was jointly organized by GSP, ITPS, GSBI and the UN Convention on Biological Diversity (CBD) and the Science-Policy Interface of the United Nations Convention to Combat Desertification (SPI - UNCCD) and held in April 2021, there are seven recommendations for future work. The first two of these are relevant for soil biological indicators in the EU (FAO 2021). The first recommendation concerns the establishment of the Global Soil Biodiversity Observatory (GLOSBO). The main objective of GLOSBO will be to strengthen knowledge in all soil biodiversity groups and areas of work should include/strengthen: taxonomy, novel technologies for species identification and quantification, standard operating procedures (SOPs), soil biodiversity mapping, soil health indicators, bioremediation, restoration of degraded soils, and soil microbiome. The second recommendation addresses development of guidelines for measuring, assessing and monitoring soil biodiversity The guidelines should include ad hoc standard field and laboratory protocols for measuring biological activity and biological diversity (including novel technologies), ad hoc standard protocols for mapping soil biodiversity at farm and national scale (with an emphasis on hot spots and not studied areas) and ad hoc standard protocols to analyse soil biodiversity data/information. The implementation of these recommendations would greatly benefit inclusion of biological indicators in SQ monitoring within Europe.

IPBES

Also at the global level, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) is to perform regular assessments of knowledge on biodiversity and ecosystem services. Addressing an invitation by the Conference of the Parties of the Convention on Biological Diversity (CBD), this intergovernmental body has compiled a global assessment of biodiversity and ecosystem services, building on its own and other relevant regional, subregional and thematic assessments, as well as on national reports (IPBES 2019).

Typically, IPBES discriminates for ‘Nature’s Contributions to People’ (NCP), which are considered more considerate of the social aspects of ES than the conventional ES approach (Pascual *et al.* 2017, see page 22). On the basis of availability of global data, prior use in assessments, and alignment with the NCP, soil organic carbon has been used as an indicator for NCP 8 ‘Formation, protection and decontamination of soils and sediments’ (IPBES 2019). Other than this parameter IPBES has made no use of soil quality data, and selected indicators for soil-related NCPs are generally at a higher abstraction and landscape level, e.g., ‘Extent of agricultural land—potential land for food and feed production’ as indicator of the NCP 12 ‘Food and feed’, and ‘Extent of natural habitat in agricultural areas’ for NCP 10 ‘Regulation of detrimental organisms and biological processes’ (IPBES 2019). The IPBES Land degradation and restauration report also identified soil organic carbon as soil organic carbon as an indicator of soil health (IPBES 2018). Other indicators that have been identified in this report refer to soil and land degradation processes rather than soil quality and ES provision, e.g. organic matter decline, land cover, green biomass production, or species distribution as an indicator of habitat loss.

The global assessment has established as one of the most important knowledge gaps: quantitative syntheses of the status and trends of parasites, insects, microorganisms, and biodiversity in soil, and of the implications for ecosystem functions (IPBES 2019 p.209).

5.8.2 Stakeholder participation

The above international stakeholders have been reviewed for their involvement in setting the stage for SQ monitoring, either by formulating environmental policy or by their involvement in the assessment of environmental quality and ES. That is not to imply that national stakeholders would be considered less important. SIREN simply did not have the means to review the relevant national stakeholders in Europe, except by superficial means via the Questionnaire asking the Partners for the knowledge needs and priorities in their countries (Chapter 4). However, we consider the participation of stakeholders crucially important in the development of national SQ monitoring programs, and below we elaborate why.

At the local and regional level, national stakeholders need to be involved at some point in the process of developing and implementing SQ monitoring schemes, not only because they are practically involved as actors or consultants in soil management, but also to ascertain acceptability and practicality of policy objectives and instrumentation. Below, the process of stakeholder participation in the development of a national soil monitoring scheme is exemplified for The Netherlands[22].

In 2018 the Dutch Minister of Agriculture launched the Dutch Soil Strategy[23] with the ambition to have all agricultural soils under sustainable management in 2030. Furthermore, the climate agreement added the challenge of realising an annual 0.5 Mton carbon sequestration to Dutch agricultural soils. These ambitions provided the foundation under the National Agricultural Soils Program (NPL), a program with the ambition to commit public and private parties to the target "all Dutch agricultural soils sustainably managed in 2030". The Program works along the following principles:

- developing and sharing knowledge as a basis for the programme;
- arrive at unambiguous and practical instruments for measuring soil quality
- identify and monitor measures for sustainable soil management;
- linking up with practice and existing initiatives;
- make sustainable soil management economically attractive.

The NLP is an ambitious program, the success of which will depend on the involvement of various parties with a wide range of interests. Hence an independent initiator of the NPL was assigned with the task to come to joint commitment between parties, and to translate commitment into concrete joint efforts of private and public parties outside central government. Given the broad range of interests, this independent initiator started with several rounds of discussions with the different stakeholders to identify their needs. It was concluded that:

1. standardized determination of soil quality is important,
2. a baseline measurement on both the current condition and the potential of agricultural soils in the Netherlands using this indicator set is needed.

These two points are important to define sustainable management and what is optimal function of a soil. By measuring and knowing which actions are targeted in more sustainable management, customization is possible, and that increases the action perspective of farmers and other soil managers.

Meanwhile, soil scientists and consultants had performed an inventory of soil quality indicators and associated parameters, working to integrate different approaches to measure soil quality. The identification of a single unique indicator set accepted by all stakeholders however was challenging, since soils may differ widely and it was a preambular that measurement of soil quality should reflect land use and soil functions. Therefore, the development of an assessment framework for soil quality was set up to follow a stepwise approach, working with consecutive 'versions of an indicator set'. These versions provide a scientific foundation for measuring soil quality, while allowing for flexibility to adapt and refine selection of soil parameters and measurement techniques. The identified parameter set 'BLN 1.0' (Hanegraaf *et al.* 2019), including reference and threshold values, was

[22] The input for this section by Saskia Visser (program director of the knowledge development program 'Circular and Climate Neutral Society' at WUR) is gratefully acknowledged.
[23] Soil Strategy Letter to House of Representatives (in Dutch) http://edepot.wur.nl/450865

proposed to a large stakeholder network. In a letter to the minister of agriculture[24], the independent initiator announced that a 43 parties large group of stakeholders endorsed the Soil Indicators for Agricultural Lands in the Netherlands (BLN 1.0) and were actually going to apply them to determine the soil quality of agricultural soils. This enhanced the applicability of the BLN for obtaining an integrated picture of site-specific soil quality. The Dutch Parliament endorsed the use and further development of the BLN[25]. A broad reviewing process with stakeholders then resulted in the BLN 1.1 and a description of a further, short-term development roadmap towards BLN 2.0 (de Haan *et al.* 2021).

The take-home message of this process is that the combination of science and policy alone was not sufficient to reach consensus and acceptability amongst stakeholders on indicators and threshold values for soil quality assessment. The independent initiator of the program played a crucial role in finding common ground amongst all soil stakeholders to facilitate the process of development towards a monitoring scheme. The stepwise development approach including iterative stakeholder participation contributed to a smooth process of adoption of the BLN 1.0.

5.9 Implementation

Since 1985, ISO TC 190 (Soil Quality)[26] has developed and validated nearly 200 standard methods to harmonize vocabulary, describe and sample soils, measure different soil biological and physico-chemical attributes and develop assessment methods. In the last years, ISO installed a working group dedicated to the assessment of soil functions and ecosystem services provided by soils with the following scope: "*establish concepts, agree definition of terms, and develop guidance documents, standards, frameworks and assessment methods".* More recently, the Global Soil Partnership (GSP) addressed the harmonisation of soil quality monitoring in order to increase accessibility and promote the use of standardized methods: harmonization of methods, measurements and indicators for the sustainable management and protection of soil resources, including the harmonisation of methods, indicators and evaluation methods (VonHögen-Peters and Blauw 2019). We address these aspects in the following sections.

Harmonisation of indicators for SQ (not methods)

Since 20 years, several projects and initiatives (e.g. ENVASSO, Landmark, SOIL4EU) underlined the existing difficulties to compare and share data from national soil monitoring networks and thus to develop common indicators. Within EJP SOIL, WP6 identified the technical issues (main differences between monitoring systems) and possible ways of harmonization/collaboration, at least with LUCAS (Land Use/Cover Area frame Survey) campaigns. It appears that with few exceptions, the countries involved in EJP SOIL do not want to change their protocols (from the design to the analytical part). 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/analyses to compare their results with LUCAS ones. Such situation is quite normal as there are quite old monitoring networks, with several campaigns 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 as it was said by one of our colleagues "*lots of MS struggle each year just to maintain their existing soil monitoring system!".* Based on those

[24] 'Brief overleg over het Nationaal Programma Landbouwbodems' (In Dutch) https://www.rijksoverheid.nl/documenten/kamerstukken/2020/09/04/brief-overleg-gevoerd-over-het-nationaal-programma-landbouwbodems and https://open.overheid.nl/repository/ronl-65d5a49a-480b-4c31-972c-ecdb7611d5aa/1/pdf/bijlage-nationaal-programma-landbouwbodems.pdf

[25] 'Bodembeleid; Brief regering; Reactie op brief 'Afspraken ketenpartijen' en voortgang Nationaal Programma Landbouwbodems' (in Dutch)

[26] https://www.iso.org/committee/54328.html

conclusions, several options were proposed from the full integration and harmonization of MS monitoring systems and LUCAS to a better collaboration between MS and EU-JRC to produce a coherent information on soils, even if data stay separate. An intermediate solution could be that data from MS and LUCAS will populate the EU Soil Observatory (EUSO) finding a way to work on data even if not obtained in the same way. Those options will be tested in the coming two years to identify advantages and limitations (Bispo *et al.*, 2021).

Protocolisation and Standardisation of methods

Either in the ISO or GSP (see Glosolan initiative) groups the aim is to agree on a common procedure. Generally, a first draft of the protocol and/or the assessment procedure is developed and submitted for review. Based on the comments, the initial document was improved and tested in an interlaboratory comparison, mainly for analytical protocols. According to the results, a final document is submitted for a last review before being adopted. Such procedures ensure a large consultation step in order to find an agreement so that the proposed protocol will be shared and used. By experience, the adoption of a new protocol will mainly depend on the existence of similar previous protocols / procedures implemented in the countries: if the standardized method is new then the chance to be adopted is rather high (i.e. no existing protocol), whereas if measurement of one particular parameter has already been implemented in different countries using different methods, then the chance for adoption decrease if no legal requirement pushes the new standard. Solving such difficulties will require the development of pedotransfer functions to pass from one method to another (Hu *et al.*, 2021).

Tiered approach in SQ monitoring

In the following we describe the approach explaining how this may deal with harmonization and standardization issues in EU monitoring, which has been synthesized and summarised earlier in chapter 3 as a charcoal-sketched proposal reflective of inputs from the Questionnaire and EEA discussion.

In monitoring and assessment activities a stepwise and tiered approach is a common strategy to break down complex problems and decisions by collecting information in a stepwise approach. This is usually done from an aggregated level down into more detail (as in natural accounting), often triggered by some threshold condition being surpassed and the gravity of the situation and the most likely causes being clarified sequentially by deduction and validation (as in environmental risk assessment). The approach could be taken as an example from other areas where it has been used successfully, and has indeed been suggested for soil monitoring:

- Environmental effect assessment of chemicals (Diepens *et al.* 2016), environmental impact assessment (Bruinen de Bruin *et al.* 2015), and brownfields and contaminated land remediation (Pediaditi *et al.*, 2005; Pollard *et al.*, 2004).
- National greenhouse gas inventories (IPCC 2006)
- Forest monitoring in EU (Nesha *et al.* 2021)
- Various methods for mapping ES (Grêt-Regamey *et al.* 2015; Maes *et al.* 2016, Burkhard and Maes 2017, Maes *et al.* 2020 (REF)
- Ecosystem extent accounting (EEA 2018b)
- UK soil monitoring network design (Black *et al.* 2008), soil monitoring system for Europe (Kibblewhite *et al.* 2008), soil biodiversity monitoring in EU (Bispo *et al.*, 2009), Scottish soil monitoring (Aalders *et al.* 2009), French soil monitoring network (Arrouays *et al.*, 2002)

A tiered approach to SQ monitoring is one that uses the simplest techniques first and advances to more detailed approaches only where necessary. This is aimed to produce information at minimum expenses with optimum degree of harmonization across countries to facilitate pan-European comparison and analysis. The tiered approach also allows stakeholders to identify where greater informational effort is required, by allowing points of already existing consensus to be identified, thus avoiding greater detailed effort on those points.

The essentials of a tiered approach are:

- Low tiers are extensive, with few, simple indicators used at relatively low-cost, relatively few sites, and top-soil only;
- A 1st tier is harmonised among countries for indicators (not necessarily standardised for methodology, leaving room for continuity in national traditional methods and trend data comparability);
- Higher tiers build on lower tier info (related data use), collecting more detailed and specified data, addressing specific national (regional, local) situations, reducing uncertainty, enhancing causality for assessment and decision-making.

A crucial question is whether SQIs in a low tier should already be feasible for application in ES assessment, or that higher tier data may be used to that purpose where needed (by specific stakeholders, not EU). Clearly, for harmonised assessments across EU only 1st tier data may qualify. But this applies to assessment of potential ES, whereas actual use and flow of services is defined at local or regional scales, involving stakeholder demand, and will make use of local / regional data anyway. A basic question here is whether NEAs should be comparable amongst countries, addressing the same ES? This is likely to be asking too much in terms of harmonisation and standardisation of SQIs...!

Desirable number of tiers

In the examples of tiered approaches enumerated above, the number of tiers is between two and four, with most approaches featuring three tiers. In the national greenhouse gas inventories, the three tiers are related to different scales, namely broad continental, country specific, and region/local specific (IPCC 2006). Three tiers related to scale in a similar way would also be a practically desirable number of tiers for SQ monitoring.

5.10 SQI evaluation and selection

We developed a summary table in order to select the most policy-relevant SQ indicators that were compiled on the basis of literature review, European projects usage, stakeholder views and inclusion in national regulations (EJP SOIL stocktakes)(Table 13). Generally, international policies call for indicators at a higher level aggregation and do not specifically identify SQIs to be used, but rather the condition that needs to be accomplished, *e.g.* no net loss of carbon, no net loss of biodiversity, or zero erosion.

To select the SQIs, we developed the following methodology:

- Based on the EJP SOIL WP2 stocktake (1st column) we identified parameters that are currently measured in at least 50% of the countries (in red, indicating that such parameters are well established or may be easily implemented);
- We then confirmed their usefulness by looking at the results of the review papers by Bünemann *et al.* (2018) and Valani *et al.* (2020) (columns 2 and 3), and by checking for recommendation by the SoilBON projects and application by the three reviewed EU research projects (columns 4 and 5);
- Finally, we established the policy and stakeholders needs (columns 6 and 7).

By doing so, we identified the main recommended indicators (red lines in the table) (currently used, validated by the literature and needed for policies):

- Soil physical status (Texture, Porosity and Bulk density)
- Soil fertility (C concentration[27], Total N, P, K, pH any form)

[27] Considering that C stocks can be calculated when combined with bulk density data.

- Erosion evaluation (calculation)
- Electric conductivity [linked to salinity]
- Trace elements

With this objective selection strategy, we missed indicators for soil biodiversity, organic contamination and water regulation/filtration. These were insufficiently common amongst countries and did therefore not “surface”. Since information from such indicators is needed by policies and stakeholders, scientifically sound and supported by research we recommend to include such type of indicators in the 1st tier minimum dataset. Based on our stocktake, however, it is not possible to select specific indicators without introducing subjectivity. We expect that current developments in running EJP SOIL projects (e.g. SERENA, MINOTAUR) will help in further selecting relevant indicators within these categories, e.g. based on novel, affordable technologies such as DNA sequencing and organic contaminant fingerprinting.

Table 13. Evaluation of SQIs implemented in EJP SOIL MS monitoring programs (established by stocktake T2.4.2) for wide application in scientific studies (literature review), EU projects, and as called for by policy and stakeholder institutions. SM, Soil Mission.

SQI Parameter	T2.4.2 (% countries) 24 countries	Bünemann (% studies) 65 SQ assessments	Valani (% studies), 92 SQ in integrated systems	SoilBON priority EBV, Guerra 2021	European research projects (3 projects)	Int. Policies (#)	Stakeholders (JRC, EEA, FAO, IUCN, GSBI, IPBES)
Texture	100	44		x	1	2	
Stoniness	50						
Porosity	58	18	45		2		
Bulk density	83	53	66	x	3	3	1
Aggregation		17		x			
C concentration	96	91	68	x	3	6	3
C stock	71		6	x	2		
SOM quality	42				1		
Labile C and N		13					
C and/or N fractions			28				
Nutrient content						2	1
Total N	83	40	26	x	3		2
Other N forms	67	29		x			
P	92	74	39	x	1		2
K	92	49	39		1		1
Ca	83						
Mg	88				1		
Other macronutrients (Mg, S, Ca)		16	40				
Micronutrients		15	6				
B	63						
Cu	79						
Fe	38						
Mn	79						

Table 13. Evaluation of SQIs implemented in EJP SOIL MS monitoring programs (established by stocktake T2.4.2) for wide application in scientific studies (literature review), EU projects, and as called for by policy and stakeholder institutions. SM, Soil Mission.

SQI Parameter	T2.4.2 (% countries) 24 countries	Bünemann (% studies) 65 SQ assessments	Valani (% studies), 92 SQ in integrated systems	SoilBON priority EBV, Guerra 2021	European research projects (3 projects)	Int. Policies (#)	Stakeholders (JRC, EEA, FAO, IUCN, GSBI, IPBES)
S	54				2		
Se	46						
Si	38						
Zn	75						
Other	42						
pH any form	92	82	44	x	1	2	1
pH active	*83*						
pH potential	*75*			*x*	*1*		
Acidification	*79*						
Cation exchange capacity	83	32			1		
Base saturation	79						1
Salinity	33	15			3		1
Electric conductivity [Salinity]	58	33	2		2		
Water content						2	
Infiltration	17	15	4				
Water field capacity	54						
Wilting point	42						
Available water capacity	46						
Hydraulic conductivity		20	4				1
Groundwater table depth					1		
Soil resistance measurement	21	26	35		1		
Soil compaction evaluation	54						
Soil structure measurement	54						

Table 13. Evaluation of SQIs implemented in EJP SOIL MS monitoring programs (established by stocktake T2.4.2) for wide application in scientific studies (literature review), EU projects, and as called for by policy and stakeholder institutions. SM, Soil Mission.

SQI Parameter	T2.4.2 (% countries) 24 countries	Bünemann (% studies) 65 SQ assessments	Valani (% studies), 92 SQ in integrated systems	SoilBON priority EBV, Guerra 2021	European research projects (3 projects)	Int. Policies (#)	Stakeholders (JRC, EEA, FAO, IUCN, GSBI, IPBES)
Soil structure degradation	46	29	30				
Erosion evaluation	71		1		2		1
Soil depth		29					
Contaminants						3	2
Heavy metals		21			2		
Al	25		32				
As	63						
Cd	83						
Co	79						
Cr	79						
Cu	83						
Hg	63						
Ni	83						
Pb	79						
Zn	83						
Other	75						
OCPs	33						
PAHs	46						
PCBs	33						
Other Organic Pollutants	38						
Soil biodiversity						3	5
Soil respiration	29	28	10	x	2		1
Potential N mineralization	17	26	4	x			
Fungal biomass	21			x	1		

Table 13. Evaluation of SQIs implemented in EJP SOIL MS monitoring programs (established by stocktake T2.4.2) for wide application in scientific studies (literature review), EU projects, and as called for by policy and stakeholder institutions. SM, Soil Mission.

SQI Parameter	T2.4.2 (% countries) 24 countries	Bünemann (% studies) 65 SQ assessments	Valani (% studies), 92 SQ in integrated systems	SoilBON priority EBV, Guerra 2021	European research projects (3 projects)	Int. Policies (#)	Stakeholders (JRC, EEA, FAO, IUCN, GSBI, IPBES)
Bacterial biomass	21			x	1		
Microbial biomass	25	26	19	x			
Macro edaphon	13		16				
Micro edaphon	13						
Meso edaphon	17				1		
Earthworms	25	15			3		
Nematodes	21			x	1		
Collembolans					2		
Enzymes	21		8	x			
Other	42			x			

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Appendix 1. SIREN Consortium Partners and persons contributing to the answering of the Questionnaire

EJPSOIL Partner #	Country short name	Partner institute	Persons contributing to SIREN
P1	FR	INRAE	Isabelle Cousin, Antonio Bispo ; David Montagne (LTP ATP), RNEST (French Network for Scientific and Technical Expertise on Soils)
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P4	BE	EV-ILVO	Greet Ruysschaert; Katrien Oorts (LTP VPO, Flanders Department of Environment and Spatial Development)
P5	BE	CRAW	Bruno Huyghebaert
P6	CZ	CZU	Janků Jaroslava, Josef Kozák, Borůvka Luboš
P7	DK	AU	Per Schjønning, Lars Juhl Munkholm
P8	EE	EMU	Liia Kukk, Alar Astover
P9	FI	LUKE	Mika Tähtikarhu (born Turunen)
P13	IE	Teagasc	Lilian O'Sullivan, Fiona Brennan
P14	IT	CREA	Silvia Vanino, Maria Fantappiè, Rosario Napoli, Chiara Piccini; Brenna Stefano (ERSAF), Costanza Calzolari (CNR), Francesca Assennato (ISPRA), Mulè Paolo (AGRIS)
P15	LV	UL	Raimonds Kasparinskis, Baiba Dirnena, Kristine Afanasjeva, Olgerts Nikodemus, Imants Kukuls
P16	LT	LAMMC	Dalia Feiziene
P17	NO	NIBIO	Alice Budai, Kamilla Skaalsveen, Erik Joner
P18	PL	IUNG	Bożena Smreczak, Agnieszka Klimkowicz-Pawlas
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P20	SK	NPPC	Jarmila Makovníková, Jaroslava Sobocká, Boris Pálka
P21	SL	UL-BF	Metka Suhadolc ; Borut Vrščaj (LTP AIS), Petra Božič (Slovenian Ministry of Agriculture, Forestry and Food)
P22	SP	INIA	Sara Sánchez Moreno
P23	SE	SLU	Astrid Taylor, Katharina Meurer, Maria Viketoft, Loraine ten Damme, Jan Bengtsson, Thomas Keller, Anke Herrmann, Rebecka Thorslund
P24	CH	AGS	Gina Garland, Olivier Heller, Peter Weisskopf, Anina Gilgen, Jerome Frei, Gudrun Schwilch, Basil Oberholzer
P26	UK	AFBI	Dario Fornara, Jonathan Holland