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European Joint Programme

Towards climate-smart sustainable management of agricultural soils

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1. Introduction to EJP SOIL Roadmap

> *"Climate change and environmental degradation are an existential threat to Europe and the world. To overcome these challenges, Europe needs a new growth strategy that will transform the Union into a modern, resource-efficient and competitive economy, where there are no net emissions of greenhouse gases by 2050; economic growth is decoupled from resource use and no person and no place is left behind. The European Green Deal is our plan to* ***make the EU's economy sustainable.*** *We can do this by turning climate and environmental challenges into opportunities and making the transition just and inclusive for all."*
>
> *Green Deal Vision of the European Commission*[1]

The Green Deal is a major policy step towards a sustainable society and acknowledges the large role soils have to play in solving the problems of our time. The Green Deal has listed a set of targets to be reached by 2050 that have a direct link to soil: i) to reduce the use of chemical pesticides by 50%; ii) have at least 25% of EU agricultural land under organic farming and a significant increase in aquaculture; iii) reduce nutrient losses by at least 50% while ensuring no deterioration of soil fertility and reduce the use of fertilisers by 20%; and iv) bring back at least 10% of agricultural area under high-diversity landscape features. The main advocates for the importance of soils are the EU Mission A Soil Deal for Europe, the EU Biodiversity Strategy, the Farm to Fork Strategy, the 7th EAP "no net land take by 2050" initiative, the forthcoming EU Action Plan for Zero Pollution, the new Common Agricultural Policy and climate change policies recognizing the importance of soils.

Recent publications by IPBES (2018, 2019), ITPS (2015), ECA (2018) and IPCC (2019) have stressed that current soil and land degradation are seriously threatening our societies. They also say that soils are a major part of the solution. The current challenge for the scientific community is to focus on research for solutions to the societal issues of our time together with a broad range of soil stakeholders. Achieving this will require interdisciplinary collaboration and dialogue between scientists and stakeholders.

The European Joint Programme SOIL (EJP SOIL) has defined as its main objective the creation of an integrated framework for agricultural soil research in Europe to foster climate-smart sustainable agricultural soil management. This framework aims to overcome the current fragmentation of research and unleash the potential of agricultural soils to contribute to climate change adaptation and mitigation while preserving or even enhancing their performance in relation to their agricultural, health, and environmental functions. Long term expected impacts of the EJP SOIL are to lead to significant long-term alignment and implementation of soil-related research strategies and activities at national and EU level, to

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[1] https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

strengthen the role of the farming sector as a steward of land and soil resources, to increase its capacity to adapt to climate change and contribute to climate change mitigation and improve carbon sequestration. These expected impacts are coherent with those of the proposed EU Soil Strategy for 2030, the EU Mission A Soil Deal for Europe, the JRC, and the European Soil Observatory.

This roadmap describes a vision for climate-smart and sustainable agricultural soil management that contributes to climate change mitigation and adaptation, sustainable agricultural production, healthy soils and landscapes and functions as a strategic agenda for the activities of EJP SOIL. This vision and agenda is based on an inventory of knowledge needs among EU soil stakeholders. Realising the ambitions of the roadmap will inform decision-making in science, policy, and practical implementation of soil knowledge. EJP SOIL has five target groups: i)EU policymakers, responsible national/regional policymakers and international stakeholders, ii) the scientific community; iii) civil society & general public, iv) farmers & advisors, landowners and managers, soil and farmer organisations (practitioners), and v) industry and agro-business.

In the consultation process, the first three stakeholder groups were involved. The last stakeholder group will be involved through dissemination and outreach activities. The roadmap leads to an implementation plan, as successive annual work programmes, that will engage Member States and stakeholders across Europe in joining forces to collaborate on soil research and complementary activities for agricultural soil management. At the end of the programme, a 10-year soil research roadmap will be delivered.

Reading guide

The purpose of this roadmap is to identify research, research capacity and infrastructure strengthening activities to be implemented by the consortium to reach the EJP SOIL objectives and contribute to the achievement of the short and long-term expected impacts of the EJP SOIL. These activities will be implemented as the tasks in the work packages and research projects that will be called for in funding calls. The document is organized as follows:

- Chapter 2 addresses the vision of the EJP SOIL and the adopted theoretical frameworks: i) a knowledge framework to put knowledge to use; ii) connections between sustainable soil management practices, soil functions, and the EJP SOIL research domains; and iii) an approach to account for regional diversity in Europe.
- Chapter 3 provides a general introduction to the EJP SOIL and a short overview of the methodology used to identify the European wide knowledge needs for, climate-smart sustainable agricultural soil management.
- Chapter 4 describes the activities that need to take place to contribute to the achievement of the six Expected Impacts of the EJP SOIL. The chapter starts with the rationale behind the subdivision of the research domains followed by these sections: a) an introduction explaining the importance of the research domain, b) the 'state-of-the-art' in that research domain, c) a description of the identified research gaps, and d) the required actions. Each section proposes a list of activities that will allow reaching expected outcomes and impact. These activities can become the tasks taken up in the EJP SOIL work packages or funded research projects.
- Chapter 5 provides the rationale behind the approach used for all the EJP SOIL activities with a focus on the research projects within the programme.

The roadmap annexes provide, i) the maps used to account for regional diversity within Europe (Annex 1), and ii) a list of topics identified in the roadmap with a short description of each (Annex 2).

The roadmap will be updated annually with information from within and outside the programme to identify additional research topics that will guide programme activities.

2. EJP SOIL Research Vision & Theory

> *A nation that destroys its soils destroys itself*
>
> *Franklin D. Roosevelt*

Our vision is to make soils a pivotal resource to enable a transition to a climate-smart, circular society. A long-term aspiration of the EJP SOIL is to put soil science knowledge into practise for a productive, sustainable, and climate-smart stewardship of agricultural land and soil resources. To achieve this, it is needed that the perception of the role of farmers among the general public, scientists, and policymakers is changed. In addition to that, farmers also need to change their perceptions of the potential for climate-smart sustainable farming.

To steer the work within the EJP SOIL, account for the complexity of soil, and assure inclusivity, we develop and apply theoretical frameworks for i) healthy soils and landscapes to enhance the provision of ecosystem services; ii) developing new knowledge, and sharing, storing, and using existing and new knowledge; iii) an infographic representation to depict the interdependencies between soil functions, soil management and the EJP SOIL research domains; iv) regional diversity to allow for locally adapted solutions; and, v) a common language to ensure comparability.

2.1. Healthy soils and landscapes to enhance ecosystem services

The Mission Board report “Caring for Soil is Caring for Life” states that the concept of soil health is key to sustainable development. Soil health has been defined by Bonfante *et al.* (2020) as ‘*The actual capacity of a particular soil to function, and to contribute to ecosystem services”*. This definition recognizes that soils are complex adaptive systems functioning as part of the landscape and provide ecosystem services on different temporal and spatial scales. The term ‘soil health’ is attractive because of its association with a healthy human body and a living ecosystem. The EJP SOIL aligns its actions with the vision developed in the EU Mission A Soil Deal for Europe by continuous discussions with members of the board and the supporting project Soil Mission Support (SMS).[2]

When using soil health as a concept, we need to consider both plot and landscape scales, including non-cropped surface areas and the scale of the territory where soils are connected with people and social and political organizations. The landscape and territory perspective is essential when it comes to considering positive and negative trade-offs of measures. The EJP SOIL works with scales that are sufficiently small and detailed to understand how the soil functions, but large enough to give handling perspective to end-users.

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[2] https://www.soilmissionsupport.eu

The Expected Impacts of the EJP SOIL fit well with the objectives and approach of the Green Deal[3] and the research domains of the EJP SOIL that are focused on contributing to a climate-smart agricultural system. The knowledge created under the EJP SOIL for climate-smart sustainable agricultural soil management will contribute to most Green Deal targets, in particular, i) the reduction of chemical pesticides; ii) more land under organic management; iii) reduced nutrient losses and fertilizer use, and iii) more diverse landscapes.

The Mission Board report[4] integrates the Green Deal objectives and targets and proposes indicators that support reaching them. Soil health is taken as the starting point for systemic transformations across food and bio-based value chains, from primary production to food industries and consumer behaviour. The principles of the Mission include, i) a focus on communities, ii) a systems approach that takes into account land, water, atmosphere, and soil as elements in ecosystems and landscapes with multiple demands and rural-urban relations; iii) soils delivering essential ecosystem services for various sectors; iv) soil diversity and the need for locally adapted management; v) consideration of continuous soil monitoring, and vi) soil literacy, capacity building, and training.

2.2. A framework to develop new knowledge, share, store, and use existing and new knowledge

As the main element of the research vision, we use an adapted version of the knowledge management framework formulated by Dalkir (2005; Figure 1). The EJP SOIL vision is comprised of four segments, i) knowledge development, ii) knowledge harmonization, organization and storage, iii) knowledge sharing and transfer, and iv) knowledge application. The four segments are equally important and part of a cyclic process designed to enhance the development and use of knowledge on agricultural soils (Figure 1). While the following description of the framework begins with knowledge development, the process may begin with any one of the segments.

For **knowledge development** it was necessary to identify **knowledge gaps** to address to the Expected Impacts. A series of consultations with the EJP SOIL stakeholders and reference documents (policy documents, scientific literature) serve as a basis to identify soil knowledge gaps across Europe. With **knowledge sharing and transfer**, the capacity of scientists and non-academic stakeholders will be enhanced and networks among and between scientists will be strengthened along with the links between science and society and the science-policy interface. A plan for **knowledge harmonization, organization and storage** is formulated to ensure soil data harmonization, standardization, and storage. Finally, the **knowledge application** and exploitation), will be facilitated by creating better guidelines, enhancing the science policy

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[3] https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

[4] Veerman, C., Bastioli, C., Biro, B., Bouma, J., Cienciala, E., Emmett, B., Frison, E. A., Grand, A., Hristov, L., Kriaučiūnienė, Z., Pinto Correia, T., Pogrzeba, M., Soussana, J-F., Vela, C., Wittkowski, R., *Caring for soil is caring for life: Ensure 75% of soils are healthy by 2030 for food, people, nature and climate.* Independent expert report, European Commission, Publications Office of the European Union, Luxembourg, 2020.

interface and awareness and capacity for climate-smart sustainable agricultural soil management adoption.

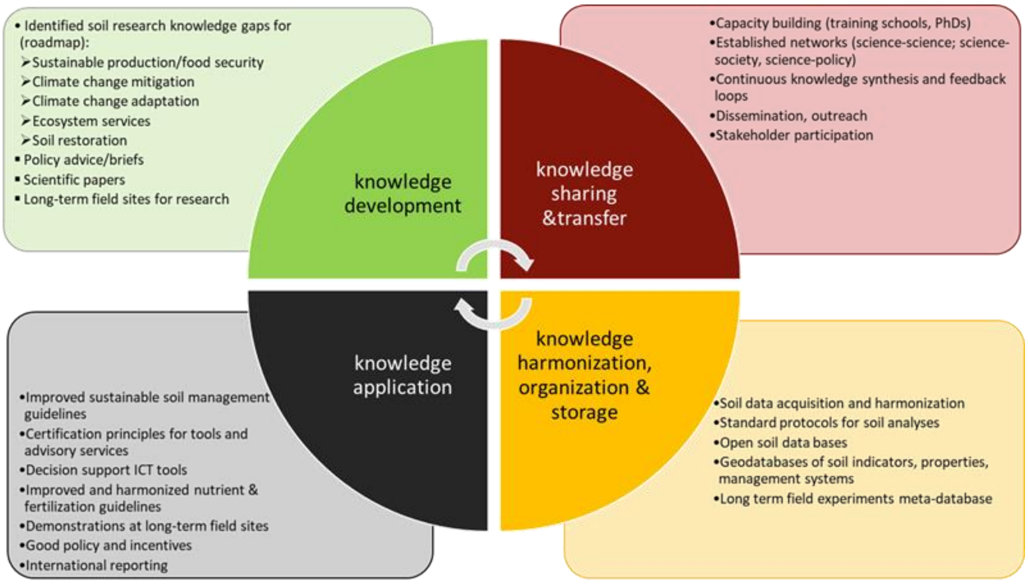

Figure 1: The EJP SOIL knowledge framework. Adapted from Dalkir, 2005. The main stakeholder groups involved can be mapped on this framework: i) policy makers: harmonization and application and sharing; ii) practitioners: application and sharing; iii) general public: sharing; iv) scientists: involved in all four compartments; and v) industry and agro-business: application and sharing. However, the different groups may provide input to other compartments of the framework (e.g. practitioners identify knowledge gaps that are picked up by scientists (see chapter 5 for more information on the role and benefits of the different stakeholder groups in the knowledge framework).

2.3. Research domains of the EJP SOIL

The EJP SOIL aims to contribute to sustainable agricultural soil management for overarching research domains that are improving climate change mitigation, adaptation to climate change, sustainable production, and sustainable environment, which comprises of biodiversity conservation, ecosystem services, and reducing soil degradation. These items will be named research domains. Because these domains are broad and interlinked, Figure 2 was designed to illustrate the multiple links between the EJP SOIL research domains and elements of climate-smart sustainable agricultural soil management and between soil challenges and the elements of climate-smart sustainable agriculture.

Seven agricultural land management categories have been designated (see the glossary on the EJP SOIL website for an overview of the different practices). Policies can directly influence the choices farmers make within these categories through mandatory regulation, economic instruments, voluntary approaches, and education and informational instruments. The day-to-day choices farmers make about farm management affect the different elements of climate-smart sustainable soil management as defined by the FAO in the Voluntary Guidelines for sustainable soil management (Baritz et al., 2018). Soil management affects soil characteristics and processes, these have an influence of soil primary functions that contribute to the climate change mitigation and adaptation, sustainable production and environmental protection. Given the threats to soils, , several soil challenges must be addressed to ensure that soils assure their primary functions and deliver the related ecosystem services. The interaction between the soil and management segments of this diagram will help identify and address the research needs essential to achieving the EJP SOIL objectives.

Figure 2 Link diagram illustrating i) how local land management choices can influence the elements defining climate-smart sustainable soil management; ii) the link between primary soil functions and soil challenges; and iii) how optimized interactions between soil functions and soil management will lead to achieving the EJP SOIL research domains.

2.4 Accounting for regional integration and diversity

Soils are the result of the climate, geology, time, and human interventions they have been exposed to. Each soil needs a different management strategy to be sustainably managed and to become or stay healthy. Policy and governance are not everywhere the same in Europe, therefore, the EJP SOIL has taken into account this regional diversity as much as possible. Two approaches have been used. The first is applying the environmental zones defined by Metzger *et al.* (2005). Based on the most relevant environmental variables grouped under climate, geomorphology, marine influence, and latitude, Europe was divided into 13 environmental zones. The second approach, simpler, is assigning countries into groups: North, West, Middle, East, and South Europe (see Annex 1 for maps). Regional diversity will be used to target research and activities.

3. The EJP SOIL methodology for a European knowledge needs inventory

The EJP SOIL aims to address it research domains and contribute to its expected impacts through joint programming of research, training and capacity building, data harmonization and science to policy activities. The consortium consists of 26 partner institutes from 24 countries. The EJP SOIL is structured around ten Work Packages (Figure 3).

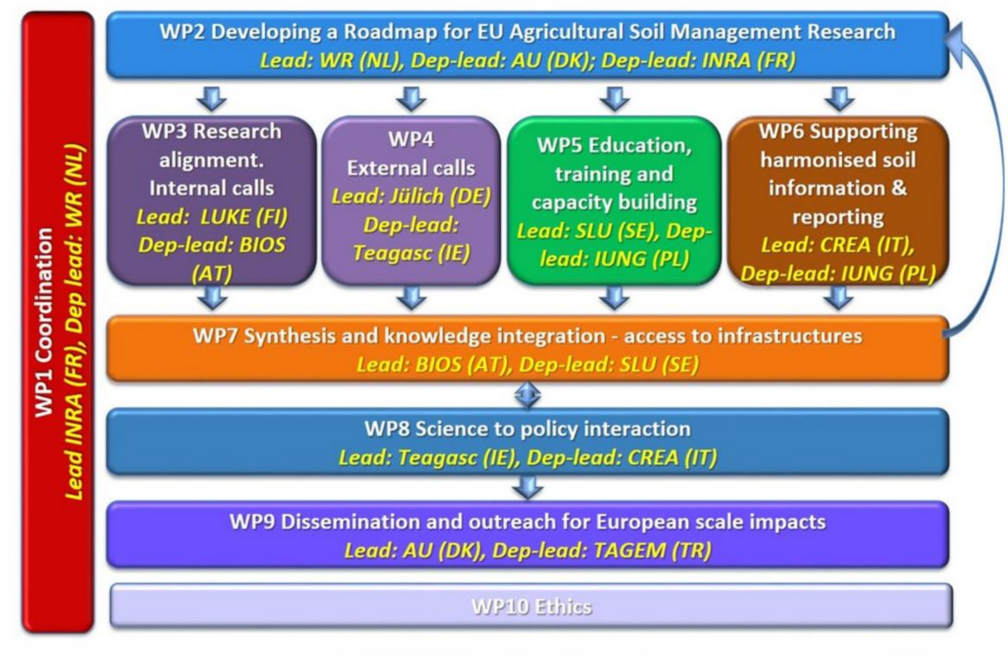

Figure 3: Structure of the EJP SOIL work packages.

3.1. A conceptual framework: expected impacts of the EJP SOIL

To feed the three long term expected impacts of the EJP SOIL ((i) significant long-term alignment and implementation of soil-related research strategies and activities at national and EU level, (ii) strengthen the role of the farming sector as a steward of land and soil resources and (iii) increase its capacity to adapt to climate change and contribute to mitigation and carbon sequestration, six expected impacts are identified which can be connected to the knowledge framework (Table 1).

Table 1: The six expected impacts of the EJP SOIL and their relation to the knowledge framework

Expected impacts of the EJP SOIL		Knowledge framework compartment
1	Fostering understanding of soil management and its influence on climate change mitigation and adaptation, sustainable agricultural production and environment.	Knowledge development
2	Understanding how soil-carbon sequestration can contribute to climate change mitigation at the regional level and accounting for carbon.	Knowledge development
3	Strengthening scientific capacities and cooperation across Europe including training young soil scientists.	Knowledge sharing and transfer

4	Supporting harmonized European soil information, including for international reporting.	Knowledge harmonizing
5	Fostering the uptake of soil management practices conducive to climate change adaptation and mitigation.	Knowledge application
6	Develop and demonstrate region- and context-specific fertilization practices (soil, water and pedoclimatic conditions).	Knowledge application

3.2. Collaboration with soil stakeholders

The EJP SOIL partners develop national programmes on agricultural soils and are involved in regional and international partnerships such as FACCE JPI, 4p1000 initiative, GSP and ESP, and collaborate in the recently funded H2020 project SMS. Despite these partnerships and initiatives, research on agricultural soils remains fragmented when it comes to addressing common European challenges as outlined in the six EJP SOIL Expected Impacts. The ambition of the EJP SOIL is to pool and align national resources and partner efforts to harmonize methods, indicators, databases, and models across Europe. This can be realised by developing a theory of change about the Expected Impacts (see Table 1) and setting a baseline through stocktaking activities, performing research in EJP SOIL projects, facilitating access to long-term field experiments, facilitated knowledge exchanges by visiting scientist grants. The EJP SOIL will rely on previous and ongoing research efforts within EU projects and invite stakeholders to the synthesis workshops, where the EJP SOIL activities and outputs will be presented and discussed, to assure coherence with major soil conventions, initiatives and networks.

The EJP SOIL promotes stakeholder involvement. Stakeholders involved in agricultural soil management are connected through participation in the National hubs where they provide inputs on national ambitions, barriers, and knowledge needs to achieve climate-smart sustainable agricultural soil management and serve as knowledge distribution points. At the European level, the EJP SOIL Advisory Board of high level scientific and societal stakeholders advises on the overall direction. Research projects with the involvement of farmers, extension services, and the general public are promoted as well as collaboration in existing Living Labs and Lighthouse Farms.

3.3. Methodology for a European inventory on knowledge needs

To assure that the EJP SOIL roadmap addresses the knowledge needs of all participating countries, a broad European inventory was conducted. Figure 4 provides an overview of the methodology followed. The process began with a European-wide consultation, integrating the knowledge needs into a roadmap, and synthesising the knowledge needs into activities for WP tasks and topics for research projects. Despite the change in planned activities due to COVID-19, all consortium partners managed to contribute to the process.

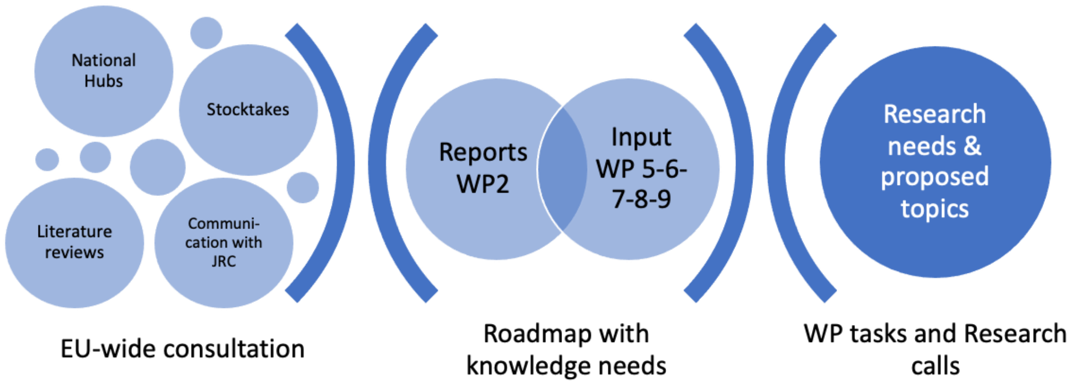

Figure 4: The methodology resulting in the selection of the EJP SOIL activities (WP tasks and research calls) based on an EU wide inventory of knowledge needs.

EU-wide inventory

Each partner made a thorough national stakeholder inventory, after which most countries established a National Hub for consultation. The stakeholders consulted represented all soil groups including academics, policymakers, NGOs and farmer organizations. A three-step approach was followed to identify the knowledge needs from across Europe.

In step 1, stakeholders were asked for their *aspirational targets*, which identified soil service aspirations at regional, national and European level for the future. This included the identification of needs for soil services and soil functions and the main drivers affecting them. Stakeholders identified the most threatened soil services depending on regional conditions and farming systems.

In step 2, *knowledge availability and use* were investigated by a review and stocktaking of current agricultural soil research activities, soil-based policies, and an assessment of the availability and use of the knowledge.

In step 3, the *barriers and opportunities* to reach the aspirational targets were identified.

Knowledge needs were identified according to the EJP SOIL knowledge framework (Chapter 2). Due to the COVID-19 pandemic, planned workshops were replaced with questionnaires and interviews with key stakeholders. The collected information is available in the reports on Tasks 2.1, 2.2.1, 2.2.2 and 2.3.[5]

Five EU stocktakesi were completed: i) the impacts of sustainable soil management practices; ii) soil quality indicators and associated decision support tools, including ICT tools; iii) estimates

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[5] EJP SOIL deliverables D2.5: Report on identified aspirations on soil services and functions; D2.6 Report with an overview of state-of-the-art knowledge of soil research soil carbon stocks, soil degradation, soil fertility, and potential improvement strategies); D2.7: Report on the current availability and use of soil knowledge; D2.8: Report on barriers and opportunities at regional, national and EU level for further harmonization and collaboration concerning research, data, training and education.

of achievable soil-carbon sequestration on agricultural land in the EU; iv) the use of models for accounting and policy support (soil quality and soil carbon); v) harmonizing methodologies for fertilization guidelines (see the respective reports)[6]. In WP6, information was gathered on the harmonization of soil information and related methodologies. To complete the stocktakes and define the state-of-the-art, a set of short literature reviews were undertaken on a range of topics not specifically addressed in the other WP tasks.

Roadmap and a prioritized set of the EJP SOIL activities

This wealth of information was incorporated into the current roadmap. The roadmap has chapters for each Expected Impacts. Chapters start with a description of the state-of-the-art which, combined with the identified knowledge gaps from the EU inventory result in a set of outputs and activities designed to deliver the outputs. Each chapter ends with a list of planned work package tasks and proposed research topics that can be developed into an internal or external call for projects. Annex 2 combines all topics and briefly describes them. The EJP SOIL partners and the different the EJP SOIL boards were asked to provide feedback on these topics so a prioritised subset of topics could be developed into calls for research (WP3/WP4).

4. Expected Impacts

4.1. Preamble

To allow for an in-depth rationale leading from the state-of-the-art and knowledge gaps to identifying needed outputs, we subdivided the first Expected Impact (1: fostering understanding of soil management and its influence on climate change mitigation and adaptation, sustainable agricultural production and environment) into four components, along with the identified research domains (Figure 5).

We also considered that fostering the uptake of climate-smart sustainable soil management (Expected Impact 5) required outputs related to adoption by end-users such as extension services and science-policy interfaces (Figure 5). We grouped Expected Impact 6 (developing region-specific fertilisation guidelines) with Expected Impact 5 (fostering uptake of climate-smart sustainable soil management) as both focus on the adoption of climate-smart sustainable soil management. The following sections will develop the rationale between state-of-the-art and identified activities, outputs and outcomes allowing achievement of the Expected Impacts presented in Figure 5.

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[6] Deliverables D2.1 Stocktaking: impacts of sustainable soil management practices in EU; D2.2 Stocktaking: soil quality indicators and associated decision support tools, including ICT tools in EU; D2.3 Stocktaking: studies on achievable soil carbon sequestration on agricultural land in EU; D2.12: Inventory of the use of models for accounting and policy support (soil quality and soil carbon); D2.13: Stocktake study and recommendations for harmonizing methodologies for fertilization guidelines.

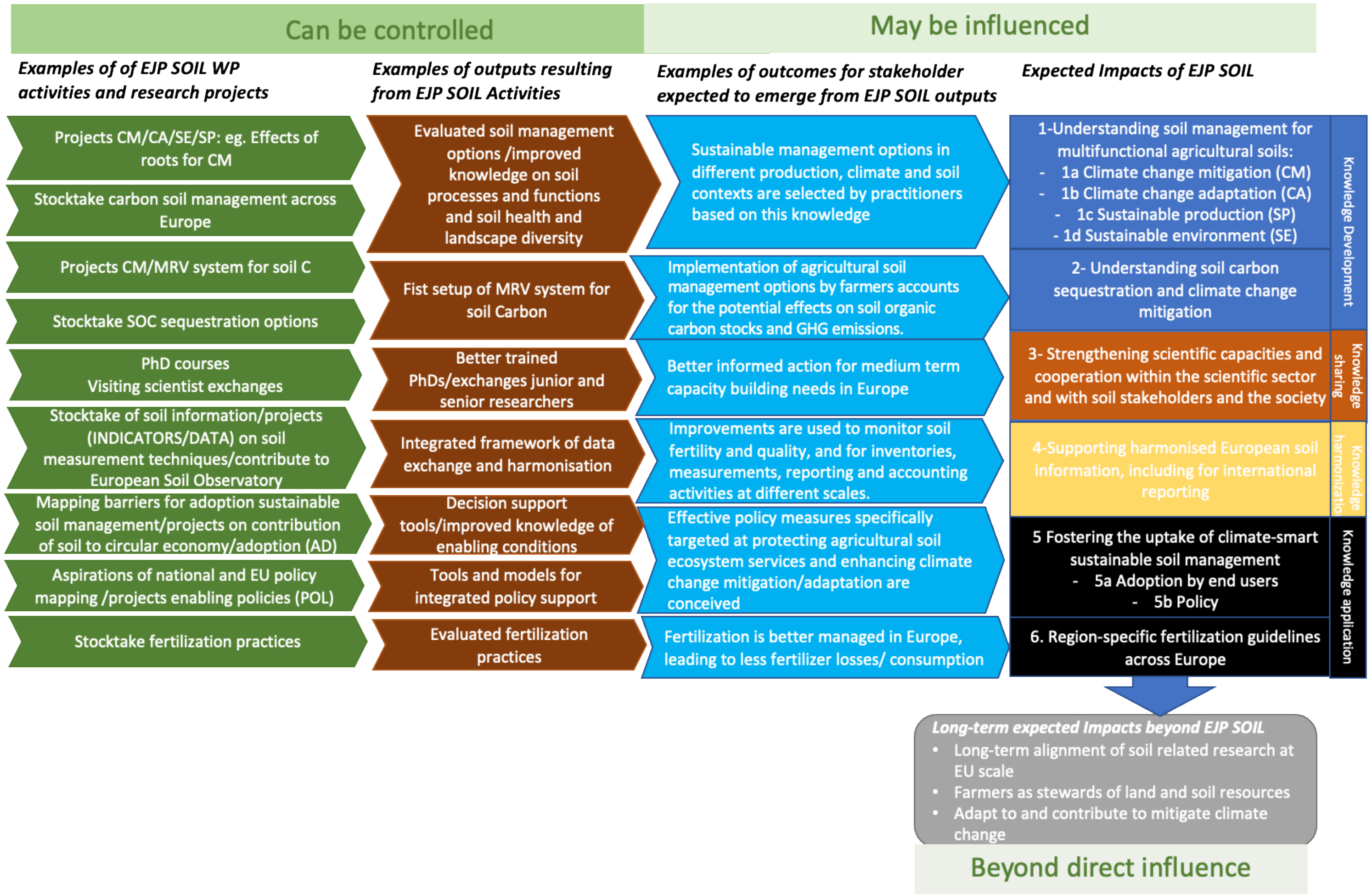

Figure 5: The EJP SOIL impact pathways logical framework. Examples of activities and outputs with concrete deliverables from the programme are given (non-exhaustive) and how they lead to the EJP SOIL outcomes and Expected Impacts and Long-term Expected Impacts. The range of influence of the programme is indicated (light green boxes). On the right-hand side of the figure the relation to the knowledge framework (Fig. 1) is given.

4.2. Expected Impact 1a and 2 - Fostering soil-carbon sequestration in agricultural soils that contributes to climate change mitigation

4.2.1 Introduction

The recent IPCC report on climate change and land stated that reaching carbon neutrality is not possible without a significant contribution via managing sinks and sources in soils in agriculture and forestry (IPCC, 2019). Soils represent the largest terrestrial reservoir of organic carbon (Le Quéré *et al.* 2018) and the balance between soil organic carbon (SOC) formation and loss is expected to drive powerful carbon-climate feedbacks. Agricultural soils have a major role to play as they have lost huge amounts of organic C since the advent of agriculture (Sanderman *et al.* 2017). Agricultural soils often continue losing C in many European locations (e.g., Goidts *et al.* 2007). Selecting the most appropriate soil management practice is considered one of the best measures to store carbon in the soil and sequester CO_2 from the atmosphere (Smith *et al.*, 2008).

In this context, agricultural management could become a main driver of CO_2 sequestration, soil C sequestration qualifying as a significant GHG removal technology at a low cost compared to other negative emission technologies (IPCC 2019). However, additional soil C storage is slow and the storage potential of soils is limited (Chenu *et al.* 2019; Bossio *et al.* 2020). In addition, risks are high and relate to the permanence of C removal, leakage, and trade-offs with other greenhouse gas emissions. Such risks need to be identified for insurance regulation and assessed in C removal payment and certification schemes, which is crucial to engaging farmers in climate change mitigation actions.

Ambitious political objectives have been set both internationally (Paris Agreement, NDCs) and at the European level (GHG emission reduction by at least 40% in 2030 compared with 1990 emission levels in EU Climate and Energy policy framework, 2018, and zero net GHG emissions by 2050 in the Green Deal, 2019). In the report “Caring for Soil is Caring for Life” (Veerman *et al.*, 2020), the Mission Board set as targets for 2030 that current SOC losses in farmlands should be reversed to an increase of 0.1 to 0.4% per year and that the area of managed peatlands losing carbon should be reduced by 30% to 50%. To contribute to these targets, we need to develop new knowledge (see Fig 1), and therefore the goal is to better understand how to foster sequestration of organic C in soils while contributing to net GHG mitigation in the agricultural sector (i.e., no trade-off with an increase of nitrous oxide [N_2O] and methane [CH_4] emissions).

4.2.2 State-of-the-art on climate change mitigation

Increasing SOC stocks in agricultural soils, in addition to the effective reduction of N_2O and CH_4 emissions from agriculture, requires progress in five areas:

1. Evaluating the effect of individual and combined soil management options on SOC sequestration and GHG emissions.
2. Providing realistic estimates for SOC storage potential across EU agricultural soils.
3. Understanding the mechanisms and drivers behind C sequestration and GHG emissions from agricultural soils.
4. Measuring, reporting, and verifying (MRV) SOC stocks and GHG emissions.

5. Creating enabling conditions for reducing GHG emissions and increasing SOC stocks and developing C farming schemes that keep landowners and farmers committed for the long term.

Evaluating the effect of soil management options in SOC sequestration and GHG emissions

Enhanced soil organic carbon (SOC) sequestration may contribute to GHG emissions mitigation for decades from the following three options:

1. Preserving existing SOC stocks.
2. Enhancing the return of organic matter to soils in agro-ecosystems.
3. Making available and using external sources of organic matter.

Several estimates are available of additional SOC storage and GHG emissions resulting from land-use and land-use changes or due to agricultural soil management options and are used in regional, national and European assessments (Pellerin *et al.* 2019, Lugato *et al.* 2014, Smith *et al.* 1998). However, most studies and meta-analyses focus on the impact of single practices or specific technologies without revealing the scope and scale of food chains or considering the broad diversity of agricultural systems in Europe. For example, conservation agriculture is much more than a group of practices that reduce the amount of tillage needed. Agricultural systems are often based on rotations or polycultures of different species. In many cases, not all measures and practices are relevant or additive. In many other cases, farmers apply strategies to fit specific needs, which may develop into integrated packages of measures. In parallel with the development of bio- and circular economies, the evolution towards alternative models of agricultural production meeting the challenges of agro-ecological and food transition emphasize the need for new assessments. The EU Farm to Fork strategy, with its the target of reaching 25% of agricultural land under organic farming highlights this need.

Evaluating the SOC storage potential in EU agricultural soils

Despite the growing interest and political momentum of the concept of SOC sequestration as a negative emission technology, only a few countries are aware of their national potential to sequester C in soils. This led FAO's Global Soil Partnership (GSP) to implement the ongoing global GSOCseq exercise. This exercise uses modelling to predict the effect of increased biomass returns to the soil on SOC stocks and builds on the previously established global GSOC map (FAO 2020). This assessment and its acceptance and adoption in practice would benefit from proven, agreed, and regionally relevant, if not uniform, SOC sequestration metrics and consideration of technically possible management options.

Understanding mechanisms and drivers of SOC sequestration and GHG emissions from agricultural soils

Knowledge of the processes regulating SOC storage and the persistence of sequestered SOC has evolved tremendously in the last decade, with a paradigm change regarding the formation and stabilization of soil organic matter (SOM) (Fontaine *et al.*, 2007; Schmidt *et al.* 2011, Lehmann and Kleber 2015). Yet, many questions remain. The integration of recent results from studies of natural ecosystems (e.g., old permanent grasslands and forest) with results from agricultural research has the potential to considerably improve and diversify soil management options for a large impact on the carbon cycle and possibly an easier adoption by farmers (Mariotte *et al.*, 2018; Glover *et al.*, 2010). This process of transforming agriculture systems (e.g., Henneron *et al.*, 2019; Wurzburger *et al.*, 2009) with the use of innovative agricultural practices from successful co-designs (Crews *et al.*, 2016; Duchene *et al.*, 2017; Schulte et al, 2016) with innovative farmers will likely bring benefits including soil carbon storage, ecological intensification of production, reduced nitrate fixation and greater biodiversity. This will facilitate adoption by farmers and acceptability by citizens. Meanwhile, prioritizing which management options to implement is still hampered by the need to understand the processes governing SOC storage and permanence and the relationship with GHG emissions other than CO_2.

Measuring, reporting and verifying SOC stocks and GHG emissions

An incomplete understanding of how climate, soil type, land use, and management regime influence SOC changes adds complexity to designing appropriate monitoring, reporting and verification (MRV) platforms at the national and farm levels. The uncertainty of slow, small-scale changes over large background stocks, as well as spatial variability and associated costs, make direct large-scale measurements of SOC stocks and their variations impractical in the short term.

In addition to the poor understanding of some of the processes of soil organic matter dynamics, it is necessary to harmonize the measuring, monitoring and reporting of SOC in Europe. Here the knowledge framework (Fig. 1) section of knowledge harmonization come into play. As European countries are heterogeneous in the way they report to the UNFCCC on SOC changes in agricultural soils using methodologies ranging from Tier 1 to Tier 3 (Smith *et al.* 2019). It is important that all countries can estimate their agricultural soil emissions to maximize transparency, accuracy, completeness, and consistency given the increased ambitions of programmes like the Green Deal and the Mission Soil Health and Food, and the reporting requirements for GHG emissions and Nationally Determined Contributions under the Paris Agreement. Credible and reliable MRV platforms are needed for national SOC stock reporting and emissions trading. At the farm scale, MRV is still difficult and not available throughout Europe. A consensus has recently been reached on the need for hybrid SOC MRV platforms by combining the use of spatial data on climate, soil, and activity with long-term experiments, soil monitoring systems, remote sensing, and modelling (Smith *et al.* 2020, Smith *et al.* 2019, Paustian *et al.* 2019).

Enabling conditions for reducing GHG emissions and increasing SOC stocks: developing carbon farming schemes

Despite its potential as a low-cost technology, soil C sequestration has not yet been adopted by many farming businesses across Europe. Knowledge barriers and the absence of specific payment and reward schemes limit its wider implementation. In many recent cases and activities, the agro-processing industry is committed to reducing CO_2 emissions from energy and transport, and removing CO_2 from agricultural production. This may lead to the development and inclusion of SOC sequestration in C markets linking the fossil fuel system with agricultural soil emissions and to carbon farming. Given its risks and non-permanent nature, the inclusion of a C credit mechanisms for soils at the farm level will need to comply with specific insurance standards, for example, the verifiability of climate change mitigation practices.

4.2.3 Identified knowledge gaps

Evaluating the effect of soil management options on SOC sequestration and GHG emissions

According to the stakeholders surveyed in T2.1,[7] agricultural systems such as conservation agriculture, agro-ecological farming, organic farming, agroforestry, and precision agriculture have the potential to maintain or increase SOC and reduce net GHG emissions, however, they are largely absent in current soil policies. According to the EJP SOIL scientists (T2.3 and Mazzoncini *et al.*, 2019), management practices requiring knowledge development are related to internal and external biomass inputs to soils in terms of location (subsoil vs topsoil), nature (exudates and root turnover), timing, and pre-treatment (organic waste and biochar). Considering the potential harmful effects of possible climate-smart soil management options such as losses of N and P by leaching, N emissions and nitrous oxide to air, and applications and use of chemicals, considerable care must be taken when selecting solutions that will work today and into the future.

Altogether, WP2 surveys highlight the potential benefits of a systems approach in which traditional disciplinary work in soil science benefits from socio-economic insights concerning farmers' economy and behaviour concerning the necessary changes in day-to-day farm decisions. Peatland management raises issues among stakeholders and scientists about the protection of peatland organic matter stocks through rewetting and alternative agricultural practices that minimize GHG losses, and protection of natural or pristine peatlands.

Evaluating the SOC storage potential in EU agricultural soils

Only a few countries are aware of their nationally achievable C sequestration potential. As part of the EJP SOIL consortium, eleven countries have assessed the achievable C sequestration in agricultural soils at the national scale, using either Tier 2 or Tier 3 methodologies, and only one has estimated the economic value of soil C sequestration potential (T2.4). An integrated approach would ensure this potential is translated into achievable and realistic sequestration figures across the EU, tailored to regional conditions, and recognized by the farming community. National estimates of biophysical, technical, economical, and achievable and realistic potentials are needed that consider both present and future climate scenarios, as well as scenarios for the development of agricultural systems and innovations and scenarios for the development of, e.g. bioeconomy, and biomass renewable energy production.

Understanding mechanisms and drivers of SOC sequestration and GHG emissions from agricultural soils

The EJP SOIL surveys identified knowledge gaps regarding the processes that determine the storage of SOC and the persistence of SOC and emissions of CO_2, N_2O and CH_4. These gaps are consistent with the frontier research domains defined by the H2020 CIRCASA Strategic Research Agenda[8] and the knowledge needs identified by the Mission Board (Veerman 2020). Overcoming knowledge gaps means, estimating the existence of upper limits to soil characteristics and exceptions if these exist, understanding the reversibility of SOC storage, in particular, with climate change and the permanence of storage in connection to SOC formation and stabilization pathways. The extent to which soil biodiversity controls SOC sequestration

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[7] These numbers refer to EJP SOIL tasks reports.

[8] https://www.circasa-project.eu

and whether this can be managed is not sufficiently known, although farming practices and agricultural systems are known to have a major effect on the soil biome and its physiology (e.g., C use efficiency). The importance of stoichiometry in controlling organic matter stabilization and the balance between SOC storage and N_2O emissions also warrants further research.

Measuring, monitoring and verifying SOC stocks and GHG emissions

An extensive assessment of stakeholder knowledge demands and needs performed by the H2020 CSA CIRCASA[9] identified SOC MRV as one of the four main categories of knowledge gaps. Mainly non-farmer stakeholders expressed the need for reliable and standardized MRV methods for SOC with sufficient statistical relevance and at a reasonable cost. The gap is not about access to available knowledge and methods, but about the development of new tools and methods.

The EJP SOIL stakeholder survey on knowledge availability (T2.2.1) identified “insufficient monitoring and the need for common monitoring systems on national and international bases” and “standardized, international, easy-to-use methods for SOC stock assessment” as two of the top ten knowledge gaps in soil C stocks. The need for progress in low-cost C measurement methodologies and accessible tools such as C balance for farmers and advisory services was also stressed. The EJP SOIL survey (T2.3) revealed that the lack of common and standard methodologies used for soil sampling analysis and mapping was the main barrier to harmonizing knowledge, organization, and storage. The need to develop an MRV system for SOC has been emphasized by UNFCCC and the Paris Agreement, the UNCCD/LDN initiative, the 4p1000 initiative, and GRA reports and the international literature.

MRV at the farm scale is largely missing. However, it can encourage farmers to engage in commitments to reduce their farm C footprint and enhance soil carbon sequestration. As a starting point, this target could be based on simple C balances produced annually by farmers or their advisers to calculate C fluxes from their set of cropping and farming operations. A simple tool could be derived from modelling exercises to yield default figures for specific crops, soil and climate conditions, and management operations. As the science progresses, these C balances could be updated over time to improve their accuracy.

Enabling conditions for reducing GHG emissions and increasing SOC stocks: developing carbon farming schemes

Carbon sequestration and climate change mitigation will mean enhancing the uptake of effective management practices. The EJP SOIL stocktakes (T2.3, T2.4) and the questionnaires and surveys conducted with stakeholders by CIRCASA H2020 CSA have shown that enabling conditions might not yet be in place.

Conditions include the certification of actions to secure the agricultural contribution and to evaluate those actions via specific payment schemes that recommend practices and measures that secure the delivery of verifiable contributions. The benefits of actions and practices have been identified along with the risks and concerns regarding the permanence of C removal and leakage as well as and trade-offs. Risks such as the permanency of C removal in leakage and trade-offs need to be identified, regulated, and insured in any C removal payment and

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[9] www.circasa-project.eu

certification scheme to enable farmers to participate, in order to make that the flow of knowledge will reach the end-users (see Fig. 1, knowledge application).

4.2.4 Activities and topics to address this Expected Impacts

Based on the knowledge gaps identified, we defined 4 categories of activities needed: (i) developing a network of long-term experiments and associated database of meta-data, (ii) developing a network of laboratories, (iii) harmonizing soil information regarding soil carbon, (iv) developing the science to policy interface regarding carbon farming and (v) research projects.

1. Developing a network of long-term experiments and associated database of meta-data: Long-term field experiments are essential resources for investigating the effect of soil management options on SOC sequestration and GHG emissions or scrutinizing the processes explaining the persistence of organic matter in soil. They are also needed to calibrate and validate soil C dynamics models. An inventory of partners long-term field experiments relevant to address, inter alia, soil organic matter issues will be built (T7.3), with an associated database of meta-data. Short visits (T7.4) will enable scientists to develop collaborations based on these LTEs.
2. Developing a network of laboratories: Similarly, a network of soil laboratories, related to the Glosolan network, will be accessible through short visits (T7.4) for scientist to learn the methods needed for analysing soil organic matter and implement intercalibration operations, whenever relevant.
3. Harmonizing soil information regarding soil carbon and developing measurement and mapping methods: Soil carbon is one of the most frequently measured soil characteristics. Harmonization activities of WP6 will address soil carbon, for which a variety of laboratory methods are being used in the different countries (see Expected impact 4).
4. Developing the science to policy interface regarding carbon farming:
   Identifying the knowledge needs of policy makers is necessary for adequate dissemination of research results. This will be performed through policy workshops at the national and European scale (WP8) and a focus will be on carbon farming.
5. Research projects: Annex 2 identifies activities to be developed as research projects, formulated as topics for the EJP SOIL calls.

Table 2: Topics for Climate change Mitigation (see Annex 2 for a short description)

Topics for Climate change Mitigation	
CM1	Plant below-ground inputs to enhance carbon sequestration.
CM2	Knowledge of potential SOC sequestration under different soils types/pedoclimatic regions (1st call).
CM3	Preserving and managing SOC in peatland and organic soils.
CM4	Understanding SOC sequestration.
CM5	Effects of the soil biome on the persistence of SOC storage and its drivers.
CM6	Stoichiometry of CNP as drivers for SOC storage and persistence and GHG emissions.

CM7	Components of a European SOC MRV platform.
CM8	Evaluating soil management options for specific objectives: Trade-offs between soil organic carbon sequestration, greenhouse gas emissions and/or N and P losses (1st call).
SP2	The use, processing and application of external sources of organic matter to mitigate climate change and improve soil health.
SE6	Soil futures: scenario modelling for assessing the potential of climate-smart sustainable soil management to provide multiple ecosystem services.
POL2	Enabling conditions for enhancing climate-smart and sustainable soil policy: schemes for payment for ecosystem services, including soil-carbon sequestration.

4.3. Expected Impact 1b - Fostering understanding of soil management and its influence on climate change adaptation

4.3.1 Introduction

This section will focus on how sustainable agricultural soil management can contribute to adaptation to climate change. Both the efficiency of sustainable soil management affected by climate change and soil functions are related to primary production, biodiversity, water, nutrients, and carbon sequestration (Abbasi *et al.*, 2020; Franke *et al.*, 2020). So far, the focus of soil management strategies has been on mitigation, particularly through carbon sequestration in the soil. Soils provide a range of ecosystem services to people (Smith *et al.*, 2018). These ecosystem services provide the basis for sustainable production in arable farming, animal production, grassland, horticulture, and fruit systems and provide conditions for a viable economic agricultural sector and cultural values for society as a whole. By ignoring adaptation, the potential of soils to increase resilience to climate change, is seldom addressed, particularly to extreme events and intra- and inter-annual variability (Guodaar *et al.*, 2020; Adamides *et al.*, 2020), and attention to climate change adaptation in policy and research and options to increase adoption of sustainable soil management is missing (Demenois *et al.*, 2020).

Adaptation to climate change refers to changes in human and natural systems in response to actual or expected climatic change and its impacts. Some adjustments may be small, but others could include a transition to a different system (Gosnell *et al.*, 2019). In simple terms, it ranges from ‘doing things differently’ to ‘doing different things’. In agriculture, the primary goals are to provide a livelihood for farmers and produce good quality, affordable food and other products for consumers. Resilience is perhaps a more appropriate aim for this study. Resilience in this chapter is based on the definitions given by Todman *et al.*, (2016), in which it is described as either ecological or engineering resilience. We mostly aim for ecological resilience, which refers to the ability of systems to tolerate and absorb disturbance without changing to an alternative equilibrium. This is important to maintain the necessary ecosystem services, functions, structures and feedback mechanisms. Following this reasoning, adaptation is about how actors influence resilience. Future soil management should take into account projected climate changes by adapting to adverse effects and exploit positive interactions. In terms of resilience in the context of sustainable agricultural soil management, we aim to keep soil functions, the structure of soil systems, and the identity and feedbacks.

1. Understanding the impact of climate change on soil functions (primary production, biodiversity, water, nutrients and carbon sequestration) and how soil management can

be used and adapted to support those functions under changing conditions, particularly to climate variability, is essential when advising practitioners and policymakers.

4.3.2 Identified knowledge gaps

The topic of adaptation is closely linked to fostering understanding of soil management and its influence on sustainable agricultural production. The main concern is how to deal with uncertainty and the erratic nature of rainfall events and with more frequent extreme events. To address changes in climate risks we propose to look at medium-term (2030) and long-term (2050) periods. For studies on the impact of carbon sequestration, longer time periods may be needed. The EU inventory done in the first year of the EJP SOIL (D2.5-D2.8) provided three broad categories of focus:

1. Water cycle regulation and erosion ,
2. Nutrient cycling and carbon sequestration to avoid land degradation and promote healthy resilient soils,
3. Farm-level soil management with a focus on primary production .

Each category is subdivided into subtopics. The topics and subtopics will influence the effectiveness and efficiency of soil management options focused on a particular soil function. For adaptation to climate change, in addition to the type of system, the consequences of climate change are also important to determine the effectiveness of management and to define possible adjustments in management. This justifies the approach to present the effects of climate change as a cross-cutting theme and to integrate or mainstream adaptation into other sections (see sections 4.2; 4.4 and 4.5). From the first-year EJP SOIL inventory, no clear knowledge gaps for adaptation emerged (D2.5-D2.8) but there was a plea for impact studies that could form the basis for adaptation and studies on the impact of climate change on soil functions and measures to mitigate impact. In this section, ‘mitigate the impact’ is referred to as adaptation, which is a response designed to moderate harm, reduce risk, overcome barriers, and exploit opportunities.

Water cycle regulation and erosion

Impact on water management includes i) the impact of higher temperatures and lower rainfall which are expected to accelerate the loss of soil organic matter and thus reduce water holding capacity; ii) increases in rainfall intensity and length of dry spells, which would lead to increased flooding, surface water runoff and erosion (Nearing *et al.*, 2004) as well as prolonged dry spells causing agricultural droughts (He *et al.*, 2017); iii) the effect of changes in the frequency of extreme events, notably heavy rainfalls and drought, and more generally, climate variability (e.g., extreme events but also seasonality and atypical succession of drier and wetter conditions; Santo *et al.*, 2014).

The relative impacts on soil and crop productivity will vary across farming systems and regions throughout Europe. Adaptation options such as drainage, irrigation, and soil erosion prevention measures are well known but need to be redesigned to fit local contexts and priorities (see chapter 4.7).

Projected increases in floods, droughts, surface runoff, and catastrophic events related to these impacts of climate change require planning and action with other areas of research including crop science, remote sensing, hydrology, and biodiversity specialists to design resilient agroecosystem. Remote and proximal sensing methods exist that may detect water deficiencies (Martinez-Fernandez *et al.*, 2016). These methods need further development and testing. Soil compaction in subsoil layers with high root penetration resistance is likely a widespread reason for limited root-zone water-holding capacity that impacts crop productivity, in particular in water-limited conditions.

Nutrient cycling and carbon sequestration to avoid land degradation and promote healthy resilient soils,

Increased temperatures and changes in hydrological regimes will impact C, N, and P cycles by accelerating the decomposition of soil organic matter, changing the period that crops develop and take up nutrients or leach nitrate into groundwater, and agrochemical runoff during peak showers. Drought may delay sowing dates or make specific crop rotations impossible and could result in bare soil for longer periods. This will also impact C, N, and P cycles by decreasing the amount of biomass returning to the soil, increasing leaching, and decreasing soil biota. A second issue that needs attention under the changing climate is the use of fertilizers. Apart from new technological insights, most fertilizer recommendations have been developed under a different climate regime and focused on the long-term average. The fact that climate variability and extreme events have changed has to be taken into account and we can learn from regions that have been under warmer climatic conditions.

The impact of climate change on the effectiveness of agricultural practices on crop production and N leaching and carbon sequestration is not clear. This also warrants a regional reassessment of practices aimed at preventing nitrate leaching. Furthermore, water and temperature have significant impacts on nutrient cycling in soils, which in turn influence carbon cycling. The adoption of new water management strategies has the potential to optimize nutrient cycling which will positively influence primary production potentially sequester more carbon.

Farm-level soil management with a focus on primary production

Soil management is one tool farmers have to respond to climate change and to increase the predictability of crop yields and incomes. It is on the farm that everything comes together and where the multiple stresses and the efficiency and effectiveness of soil management can be studied. Because the impacts of climate change are location and system specific, we need to capture the diversity in farming systems and climate stresses across Europe to define and evaluate adaptation strategies.

As a response to more resilient agroecosystems, field experiments in whole-farm management are the best way to understand the risks and benefits related to measures, such as non-inversion tillage, irrigation, different organic matter types, crop rotation, intercropping, more diverse cropping systems, agroforestry, conservation agriculture, regenerative agriculture, the prevention of soil compaction, and regulation and drainage of excess water during the growing season (FAO, 2020). It is important to look at both farm-level soil management strategies and how farming systems may need to be adapted to become more resilient. The better exploration of soil resources through plant diversity, plant and animal recycling, symbiosis, and new crops can constitute a response to climate change because of plant and animal resilience to climate variability. Sustainable soil management in such systems is important.

A farming systems approach will also allow an integrated assessment of trade-offs and synergies with other, non-primary production soil functions. Research is already underway, but the link to and integration with potential climate change impacts and the contribution to adaptation is not yet explicit. The costs and applicability of these measures are also of great importance for adoption by farmers.

4.3.3 Activities and outputs to address this Expected Impact

Activities needed to address this Expected Impact are embedded in several of the compartments of the knowledge framework (Fig.1);development of new knowledge of how climate change has impact on the agro-ecosystem is needed; but also this information needs to flow to the end-users (application) through communication (transfer) and comprehensive and economical monitoring schemes (harmonizing). The flow between the knowledge framework compartments is essential to adapt to climate change. The activities identified are:

1. Promote learning networks of farmers and researchers across all agro-ecological zones to experiment and work on innovations through collaboration in research projects and specific courses.
2. Apply risk analysis and management tools related to water management, erosion, N and P management, C sequestration, soil-borne diseases to guide policies and practices in light of the changing climate in the EJP SOIL research projects.
3. Identify region and farming system and soil-crop specific adaptation options to manage climate risks (extreme events, droughts, flooding, pests and diseases), particularly agro-ecological systems including agroforestry in the EJP SOIL research projects.
4. Evaluate how climate change affects the resilience of soil-plant systems by promoting healthy, biodiverse soils in the EJP SOIL research projects.
5. Establish links with other disciplines to monitor and evaluate progress through collaboration meetings organised by the EJP SOIL consortium.
6. Connect to other topics to mainstream or integrate climate change adaptation into other workflows as most soil management activities will be impacted by climate change (WP2, WP5, WP7, WP8 and WP9).
7. Connect to farmers, companies, and researchers to create awareness and learning networks (WP5 and WP9).
8. Enable knowledge transfer by actively learning from countries in warmer climate zones to define field level adaptation options, for example, on coping with drought (WP 2, WP7, WP8 and WP9).

Table 3: Topics for Climate change adaptation (see Annex 2 for a description of topics).

Topics for Climate change adaptation (see Annex 2 for a description of topics).	
CA1	Evaluating soil management options for the specific objective of climate change adaptation (1st call).
CA2	Identifying viable farm-level incremental adaptation options related to soil management to respond to water related impacts of climate change on agricultural soils: droughts, heavy rains and waterlogging.
CA3	Consequences of climate change and potential adaptation options on C, N, and P cycling and potential adaptation options for management.

CA4	How agro-ecological systems can increase resilience regarding climate change and how soil management is adapted (i.e., more biodiversity at all levels and intra- and inter-species cropping systems and landscape).
SP3	Agricultural systems for healthy soils and multiple goals.
POL2	Enabling conditions for enhancing climate-smart and sustainable soil policy: schemes for payment for ecosystem services, including soil-carbon sequestration.

4.4. Expected Impact 1c and 6 - Fostering understanding of soil management and its influence on sustainable agricultural production and developing region-specific fertilization practices considering the local soil, water and pedoclimatic conditions.

4.4.1 Introduction

Sustainable Production is a primary the EJP SOIL research domain. A strong focus on sustainable production is needed as the demand for food and non-food production on agricultural soils is increasing due to population growth and the growing use of biomass for bioenergy and bio-based industrial production. A 50% increase in food demand by 2050 was predicted by the Food and Agriculture Organization (FAO, 2009). Rapid population growth combined with climate change has placed food security high on the global agenda and is one of the UN's 17 Sustainable Development Goals. (SDG2: End hunger, achieve food security and improved nutrition and promote sustainable agriculture)[10]

Ensuring food security is also a key element in the EU Farm to Fork strategy[11] and the future Common Agricultural Policy (Camia *et al.*, 2018). To meet the increasing demand for biomass production, the concept of sustainable intensification has been introduced and is defined as, "a process or system where yields are increased without adverse environmental impact and without the cultivation of more land" (Baulcombe *et al.*, 2009; EC; 2017). Garnett *et al.* (2013) emphasized that a focus on yield increase per ha was too narrow and highlighted that, "food security requires as much attention to increasing environmental sustainability as to increasing productivity".

In this section, we will argue the need for sustainable intensification and why it is a reason for an increased focus on soil health. The EU Mission A Soil Deal for Europe under the EU Commission[12] states that "producing adequate quantities of nutritious and safe food, feed, fibre and other biomass for industries" is a primary motivation for an increased focus on healthy soils.

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[10] SDG2: End hunger, achieve food security and improved nutrition and promote sustainable agriculture https://sdgs.un.org/goals

[11] https://ec.europa.eu/food/farm2fork_enf

[12] https://ec.europa.eu/info/publications/caring-soil-caring-life_en

4.4.2 State-of-the-art on Sustainable Production

In the EJP SOIL WP2 stocktaking, there was a focus on providing state-of-the-art knowledge on soil challenges and climate-smart sustainable soil management strategies within the context of all four main EJP SOIL research domains that cover the wide range of soil ecosystem services. However, sustainable production was not addressed specifically when evaluating soil challenges or soil-improving management strategies. The EJP SOIL goal on sustainable production focuses on both the soil challenges limiting sustainable production and on the climate-smart sustainable soil management strategies to facilitate sustainable production (cf. Schulte *et al.*, 2014; 2019; Bampa *et al.*, 2019; Ijaz *et al.*, 2019).

As the sustainable intensification of arable production is needed at the national and EU scales, this chapter will focus on sustainable intensified production. According to the EJP SOIL stocktakes in WP2[13] the main soil challenges across countries and regions are i) maintaining and increasing SOC; ii) optimal soil structure; iii) soil erosion; iv) enhancing nutrient retention and use efficiency; v) soil sealing; and vi) enhancing water storage capacity. Soil salinization was expressed as a particular challenge in Southern Europe and Turkey in D2.6. As soil biodiversity and soil contamination are considered most relevant in a broader soil ecosystem service perspective, they will be addressed in chapter 4.5 of this document.

The soil-improving management strategies most commonly studied in the EJP SOIL countries and relevant in a sustainable production perspective are i) reduced and no tillage, ii) crop rotations and cover crops, iii) the use of organic fertilizers, iv) methods for efficient fertilization, and v) drainage systems and irrigation scheduling (D2.1). D2.6 confirmed that these strategies have received considerable attention across countries and regions within the EJP SOIL consortium. The D2.5[18] report shows that most of the expressed knowledge gaps across all the EJP SOIL research domains focus on these management strategies. Across the partnership, less attention has been given to targeted strategies addressing specific soil challenges such as controlled-traffic farming to improve soil structure or vegetated buffer strips to mitigate soil erosion.

4.4.4 Identified knowledge gaps

Soil challenges and Sustainable Production

In the stocktakes, most knowledge gaps in ‘maintain and enhance SOC’ relate to carbon sequestration and climate change mitigation. D2.6 states that knowledge gaps in ‘soil mineral SOC interaction’ are related to soil structure, productivity, and soil nutrients. For ‘optimal soil structure’, D2.6 stresses that more knowledge is needed on the impact of field traffic and livestock trampling on soil structure, soil functions and plant growth in different pedoclimatic zones; a more thorough assessment of the state of soil compaction in Europe, the usefulness of advanced methods for detecting soil compaction, and development of engineering solutions to limit the risk of compaction (e.g., lightweight robots, intelligent traffic).

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[13] D2.1: Synthesis of the impact of sustainable soil management practices in Europe; D2.5: Report on identified aspirations on soil services and functions; D2.6, Set of reports on State of knowledge in agricultural soil management and D2.7: Report on the current availability and use of soil knowledge, D2.8: Report on barriers and opportunities at regional, national and EU level for further harmonization and collaboration concerning research, data, training and education.

The D2.6 report also states that knowledge gaps in the 'persistence and natural resilience of compacted soils' is of importance from a sustainable production perspective. In relation to 'avoiding soil erosion', the knowledge gaps identified in D2.6 focus on monitoring, sensing erosion with high spatio-temporal resolution, data harmonization and storage, and improved site-specific modelling. Knowledge gaps on the 'impact of erosion on productivity' were not directly mentioned but are addressed in relation to management strategies to improve soil functioning.

For 'enhance nutrient retention and nutrient use efficiency', knowledge gaps ranged from the development of fertilization schemes recording to development of a holistic and multi-criteria approach for soil fertility assessment.

For 'enhancing water storage capacity', D2.6 notes knowledge gaps in the lack of up-to-date basic soil data to measure water storage capacity (see chapter 4.3 of this document) and insufficient knowledge on water storage capacity at the root zone level (relevant for sustainable production as well as climate adaption (chapter 4.4 of this document).

For 'soil salinization', the main knowledge gaps expressed in D2.6 are on monitoring and the impact of climate change on salinization risk.

In terms of 'soil sealing', the D2.6 report identifies a need for the development of standard procedures for quantification, evaluation of the impact of soil sealing, and the need to develop regulation on soil sealing. In relation to SP, the development of strategies for the reuse of formerly sealed soil or 'brownfields' for crop production is needed (Prokop *et al.*, 2011).

Soil management and Sustainable Production

The D2.6 report summarizes several knowledge gaps seen from a sustainable production perspective for crops and crop rotations, tillage and traffic, and organic matter and nutrients management. For crops and crop rotation, knowledge gaps on crop diversification were identified in D2.6, both in a cropping system context and more specifically in relation to multidisciplinary and comprehensive studies on means to achieve diversification (cover cropping, intercropping and perennial cropping) under different pedoclimatic conditions and with consideration of climate change.

The potential of strip cropping and nature-based and regenerative systems for crop diversification and associated multiple benefits were also identified in the literature (Exner *et al.*, 1999; Krus *et al.*, 2020; Morel *et al.*, 2020). For tillage and traffic, D2.6 outlines needs for studies on the effects of reduced and no tillage on soil functions and ecosystem services and on management practices to limit soil compaction. For organic matter and nutrients management, D2.6 stress, "a call for comprehensive studies on the effect of organic resources on soil C storage and soil quality and fertility". The latter topic is relevant from both a climate change mitigation and sustainable production point of view. The need for harmonizing methodologies for fertilization guidelines across regions is addressed in the D2.13 stocktake. For water management, D2.6 identifies a need for studies on efficient water management in a changing climate (of special relevance for Climate change adaptation, chapter 4.3 of this document).

4.4.5 Activities and outputs to address this Expected Impact

Activities needed to address this Expected Impact are embedded in several of the compartments of the knowledge framework (Fig.1); new knowledge needs to be developed on processes related to the threats to soil functions in the light of climate change (see the knowledge framework in Fig. 1). However, for sustainable production agro-ecosystems other parts of the knowledge framework also come into play. Knowledge sharing for educating and raising awareness with end-users; knowledge harmonization and application for enabling the end-users to implement the newly developed knowledge as well as bringing new knowledge gaps back to the scientists. These flows between the knowledge framework compartments is essential to make the transition to sustainable, climate resilient and productive agro-ecosystems. The activities needed to reach this Expected Impact are:

Soil challenges and Sustainable Production

1. Knowledge development on trade-offs of a selected soil management on other soil characteristics and subsequent agricultural production;
2. Knowledge development on impact of field traffic and livestock trampling on soil structure, soil functions and plant growth in different pedoclimatic zones;
3. Knowledge development on soil erosion and soil salinization measurement and modelling techniques and their impact on agricultural production;
4. Development of fertilization schemes that are climate resilient and sustainable;
5. Development of sustainable and climate resilient water and nutrient retention techniques.

Soil management and Sustainable Production

6. Develop efficient water management in a changing climate;
7. Assess how to manage main challenges (e.g., optimal soil structure) and develop strategies for improved soil management that address a range of soil challenges within the context of sustainable agricultural production; Assess potential of agricultural management practices based on natural processes (e.g. regenerative agriculture, organic farming, strip cropping etc.);
8. In an stocktaking activity, the current status of fertilization practices is outlined. Guidelines will be defined on the basis of the stocktaking activities on improving region-specific fertilisation practices.

Topics needed to address this Expected Impact and proposed calls are listed in Table 4.

Table 4: List of topics needed for Sustainable production (see Annex 2 for a description of topics).

List of topics needed for Sustainable production	
SP1	Mitigating soil compaction for sustainable production.
SP2	The use, processing, and application of external sources of organic matter to mitigate climate change and improve soil health.
FS2/MT4	Innovative soil management practices in Europe and their suitability for European farming systems (1st call).
SP3	Agricultural systems for healthy soils and multiple goals.
SP4	Innovative technologies for diversified cropping and site-specific sustainable soil management.

4.5 Expected Impact 1d - Fostering understanding of soil management and its influence on a sustainably used natural environment.

4.5.1 Introduction

Modern agriculture is contributing to continued soil degradation through its intensification of agricultural production, large-scale monocropping, the use of pesticides and herbicides, and excessive mineral and organic fertilizers. The effects are severe depletion of soil organic matter (SOM) content, accelerated erosion, reduced soil water holding capacity, loss of soil biodiversity, salinization, soil pollution, and increased GHG emissions (FAO and ITPS, 2015; EEA, 2015; 2019).

These ongoing processes prevent soils from contributing to ecosystem services such as food and fibre production, climate change mitigation, disaster management, and biodiversity-based control regulations (IPBES (2015; 2018, 2019), IPCC (2019) ECA (2018). These processes are accelerated and worsened by climate change due to more erratic and extreme rainfall and temperature variations and higher turnover and oxidation of organic matter with higher temperatures. The key to future climate-smart sustainable soil management lies in understanding natural soil and landscape processes such as soil biodiversity and sufficient soil organic matter to enable the soil to continue to fulfil its ecosystem functions.

Solutions lie with agricultural systems becoming more sustainable by ecological intensification taking benefit from natural processes. To achieve this goal, the European Commission aims for at least 25% of the EU's agricultural land under organic farming by 2030 (EC, 2020; Montanarella & Panagos, 2021). The Horizon Europe Mission on soil health and food (Veerman *et al.*, 2020) estimates the costs associated with soil degradation to be 50 billion Euro per year.

The Expected Impact 1d related to the EJP SOIL research domain of the sustainable use of the natural environment in agricultural land (Sustainable Environment; Fig. 2) under changing climatic conditions relates to SDG 15: life on land, especially Target 15.3: Land Degradation Neutrality (Cowie *et al.*, 2018). Another political target is 'no net land take' by 2050 in the EU and relates to the EU Biodiversity Strategy and the aim of the 7th Environmental Action Programme.[14] To achieve this target, we need to find different methods of climate-smart sustainable management of agricultural soils and landscapes. Approaches such as circular agriculture, conservation agriculture, regenerative agriculture, organic farming, nature-inclusive farming, and agroecology need to be assessed for sustainability under changing climate conditions. This will require scientific evidence for both biophysical impacts of improved soil health and landscapes, optimizing resource management, alleviating climate change, improving nutrient cycling, and water quality and availability and for socio-economic impacts to improve human health and economic prosperity (Keesstra *et al.*, 2018a; Visser *et al.*, 2019; Schreefel *et al.*, 2020).

Soil Health and Landscapes

Climate-smart sustainable environmental management can be approached using two viewpoints: 1) soil health and 2) landscape. Both are needed for climate-smart sustainable agricultural soil management and feed into i) an approach evaluating soil degradation in the

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[14] https://ec.europa.eu/environment/action-programme/

seven soil threat categories as defined by the EU (Jones *et al.* 2012), and ii) an ecosystem services approach and its potential for soil restoration emphasizing soil challenges in line with the reviews made in the first year of the EJP SOIL. Understanding soil processes and finding solutions using soil characteristics and processes will help adapt to changing environments.

A soil health approach is required as a basis for sustainable soil management to restore and secure the soil's actual capacity to function and contribute to ecosystem services in the long term (Veerman *et al.*, 2020). Knowledge development is needed to improve our understanding of how soil status and function relate to ecosystem services provision from the field scale to landscape scale and wider, and how soil challenges can be addressed by effective and sustainable management systems. Healthy soils have known characteristics (Doran, 2002; Jian *et al.*, 2020), three being soil biodiversity, soil organic matter content, and nutrient availability for crops. Functional soil and above-soil biodiversity play an important role in agricultural system functionality and the resilience of an agricultural system to climate change impacts (see chapters 4.2 and 4.4 of this document for details). It is important to know how land management affects soil health, specifically above and below-soil biodiversity and especially the impact of unsustainable use of pesticides, herbicides, and fertilizers.

The second approach is the landscape view. The connectivity of water, sediment, solutes and solids with associated substances attached is key to understanding how soil degradation impacts ecosystem services (Arnaez *et al.*, 2015; Saco *et al.*, 2020). Without combining knowledge on the plot scale (soil health) with the landscape view, solutions to limit soil degradation and restore soil functionality with a long-term vision will be difficult to find (Keesstra *et al.*, 2018b). Climatic changes such as more extreme rainfall events will induce more overland flow, which may lead to floods and severe erosion. Understanding the connectivity of landscapes and how these connections can be managed in agricultural land will help adapt to changing conditions. In addition to these two physical scales, the human factor needs to be taken into account. The farm scale is for agricultural soil and the most directly relevant but interactions with society must be taken into account (e.g., the circular bioeconomy; Juerges, 2018).

4.5.2 Identified knowledge gaps

During the first year of the EJP SOIL, knowledge gaps were identified and reported.[15] In several countries, stakeholders emphasised the interactions between management practices and the need for a better understanding of these interactions and potential trade-offs (cf. Visser *et al.*, 2019). More holistic perspectives and systems thinking are needed (Koehler *et al.*, 2019). In practice, soil challenges are highly interrelated with wider societal concerns, including providing food, protecting water bodies, restoring biodiversity and reducing greenhouse gas emissions. Therefore, it is important that management options and instruments are assessed with a holistic view and not adopted because of their effect on just one soil challenge. Then, management options initially designed to mitigate or adapt to climate change can have co-benefits for other ecosystem services. In all the Member States, the importance of each soil challenge was scored. Challenges highlighted as important in all regions (north, south, west, and central) were: ‘maintain and increase SOC’; in three regions: ‘enhance nutrient retention

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[15] Reports on deliverables 2.1, 2.2, 2.3, 2.5, 2.6, 2.6, 2.7, 2.8 and from the literature reviews done in the framework for creating this roadmap.

and use', 'optimize soil structure' and 'avoid soil erosion'; and in one region 'enhance water storage'; 'enhance biodiversity' and 'avoid salinization'. To focus the EJP SOIL activities, only soil challenges that scored high were followed up. Below each soil challenge is addressed separately, except 'enhance biodiversity' as it is a cross-cutting issue.

Knowledge gaps identified for the different soil challenges

Enhance water storage through the influence of agrological systems on i) infiltration capacity improving strategies at different SOC content; ii) blue and green water trade-offs at different SOC content (Hoekstra, 2019); and iii) soil storage capacity for different soil types and SOC content in the mid- and long-term. There is a need to improve our understanding of the dynamics of the hydrological properties of the soils under different SOC content and cropping systems in a changing climate for future projections of soil functions and associated ecosystem services.

Enhance nutrient retention and use in different pedoclimatic zones and for different SOC: through i) development of fertilization schemes; ii) increased insights into methods to reduce nutrient leaching and mineral fertilizer use, and iii) development of a holistic and multi-criteria approach for soil quality assessment.

Optimize soil structure through higher soil organic carbon content and alleviate soil compaction through i) improved mechanistic understanding of the soil compaction process; ii) evaluating the influence of soil compaction on GHG emissions; iii) assessing the impact of field traffic and livestock trampling on soil structure, soil functions, and plant growth in different pedoclimatic zones; iv) assessing the state of surface and subsoil compaction in Europe; and v) assessing the persistence and natural resilience of compacted soils and the potential of region-specific nature-based solutions at local and landscape scales.

Avoid soil erosion due to increased extreme events due to climate change through i) developing or improving monitoring programmes for wind and water erosion and their impacts on soil function losses and reduced climate change resilience; ii) studying the economic incentives for farmers to conserve soil resource for future generations (see impacts 3 and 5a); iii) developing soil erosion modelling by including the role of biodiversity under changing climatic conditions.

Maintain and increase SOC through monitoring and modelling changes in SOC at different scales and over several European climates and comprehensive interpretation of the link between SOC and soil structure with specific attention to the role of biodiversity in maintaining and restoring soil carbon, and through sustainable agricultural practices such as grassland and grazing management and reduced soil disturbance practices.

Avoid soil salinization by increasing our understanding of salinization processes due to the implementation of cropping systems including irrigation across Europe and under the current and predicted climate.

Knowledge gaps identified regarding soil management and climate change adaptation and mitigation and its influence on the sustainable use of the environment

Agricultural systems: i) soil monitoring programmes and modelling studies to support sustainable management decisions at the site-specific level under different climate change scenarios; ii) developing site-specific, precision agro-ecological practices to improve soil ecosystems; iii) evaluate farm-level drainage systems to minimize environmental impacts; iv) studies on the cost-effectiveness and applicability of soil-improving practices seen from a farmer's point of view; v) assess costs and benefits of management practices when quantifying potentials for sustainable agricultural systems; and vi) develop in parallel, analytic approaches (laboratory or experimental fields) at the farm scale to assess differences from controlled and real-life conditions.

Crops/crop rotations under changing climate, consequences on SOC storage: i) region and soil-specific crop diversification, including the effects of diversification at cultivar and genetic level on spatial and temporal dynamics of SOC and nutrients in the soil-plant-atmosphere system and the impact on soil functions under changing climatic conditions; ii) the potential of perennialization and optimization to provide multiple ecosystem services under changing climatic conditions (e.g., limit trade-offs of SOC sequestration on N_2O emissions); iv) impact of cropping history and crop rotations, including cover and catch crops, on soil quality and food production, with a focus on the effects of crop diversification on soil biodiversity and related soil functions. It is important to assess potential new cropping systems under changing climate conditions and learn from farming systems already adapted to dryer and warmer climates.

Organic matter and nutrients management: i) impact of grassland management in relation to SOC storage and nutrient cycling and soil biodiversity conservation; ii) assess the effects of organic amendments (manure, residues, biochar, etc.) on soil processes yielding multiple ecosystem services, namely SOC storage, GHG emissions, crop yields, nutrient losses, water availability, biodiversity conservation, and erosion control; iii) region-specific assessment of the effect of organic resources on soil SOC storage and soil quality, including soil fertility; iv) development of decision support tools for optimizing the use of organic resources; and v) improve mechanistic understanding of the impact of organic amendments (spatio-temporal dynamics, interaction with soil microbes, distribution of SOC over soil fractions), and taking account of starting material for bioproducts (e.g., biochar, digestates, compost) production and processing in SOC restoration.

Tillage and traffic: i) assess the effects of reduced tillage and no tillage on SOC storage; ii) improve region-specific knowledge on conservation tillage to mitigate SOC loss; iii) further mechanistic and quantitative understanding of tillage effects on SOC storage, N_2O emissions, soil biodiversity (abundance, functional and specific diversity), and the interaction of several factors including soil type, C and N status, and climate to support land management, ES assessment, and policy development.

Soil water management under a changing climate: i) site-specific studies on efficient water management in a changing climate; ii) developing holistic concepts for system and modelling studies on management strategies including irrigation; iii) analyse factors affecting water holding and recycling capacity for different soils and farming systems; iii) insights into drought-resistant crops and growth stage water restriction relationship for different crops and soils in areas that are newly affected by prolonged droughts due to climate change; iv) knowledge on improved water management (sub-surface drainage and tillage) in peatlands that will be engraved due to climate change; v) potential of water management for soil salinisation prevention and mitigation likely to occur more in larger areas under climate change.

Agroforestry for climate change adaptation and mitigation, and increasing the content of C in soils: i) potential of agroforestry as a soil-improving cropping system in Europe for increasing soil carbon stocks; ii) evaluation of trade-offs and synergies of ecosystem services provided by agroforestry systems at different spatial scales; and iii) potential of intercropping and pastoralism with tree crops as a climate adaptation option.

Soil restoration: i) potential of regenerative agriculture to adapt to climate change; ii) role of biodiversity in soil restoration and long-term effect of chemical farming on soil functions for increasing soil carbon stocks; iii) agricultural potential for peri-urban areas to avoid and restore sealed soils; iv) and restoration of soil health, specifically above- and below-soil biodiversity.

4.5.3 Activities and outputs to address this Expected Impact

Activities needed to address this research domain are embedded in several of the compartments of the knowledge framework (Fig.1). The work related to this Expected Impact are mainly related to the knowledge development compartment, where the understanding of soil management on the ecosystem is assessed. However, this new knowledge need to be transferred and implemented in practice (knowledge sharing and application).

1. Increased fundamental understanding of soil functioning (chemical, physical, biological), soil resilience, and quantified relationships between soil structure and functions, and the contribution of soils to ecosystem service provision across soil types, climate zones, and current and future climate.
2. Further developed and validated long-term climate-smart sustainable agricultural soil management practices to restore soil health, healthy landscapes, and healthy farms addressing the major soil challenges across EU regions acknowledging specific soil types and agricultural systems.
3. Site-specific (field, farm, and landscape scales) nature-based solutions based on ecosystem services for healthy soils and landscapes and a sustainable climate-smart society from a biophysical and a socio-economic point of view.
4. Region-specific scenarios for integrating healthy soils and landscapes for building a circular bioeconomy.
5. Assess and develop biotechnology approaches for natural (biological) pesticides and sustainable agri-pest management and circular bio-based practices and industries.
6. Seek synergy with the EU Mission A Soil Deal for Europe through the EJP SOIL organised workshops and meetings, on systemic innovation of relationships between diets, land-use practices, ecosystem services, and soil health. Elaborate on the EU Mission A Soil Deal for Europe systems approach to identify and select the necessary indicators with thresholds for climate-smart sustainable soil management (WP2, WP6, WP7, WP8, and WP9).
7. Seek synergies with the EU Biodiversity Strategy (EC, 2020) and the Convention on Biological Diversity (2021, Paris) in developing methods, criteria, and standards to describe soil biodiversity in terms of services, values, and sustainable use and include environmental footprints of products and organizations on the agricultural environment. (WP2, WP7, WP8 and WP9). Interactions in targeted workshops on soil indicators and dissemination of the EJP SOIL generated knowledge as WP activities or embedded in dedicated EJP SOIL research projects.
8. Define objectives for the restoration of degraded soils and a definition of 'good ecological status' of soils.

Review documents of international research agendas related to sustainable environments (IPBES, integration with Waste Directive, and WFD reduction targets, FAO documents, EEA) by WP2Several topics were proposed in calls to contribute to this Expected Impact.

Table 5: List of topics for Sustainable environment (see Annex 2 for a description of topics).

List of topics for Sustainable environment	
SR5	Landscape analyses: Erosion processes (1st call).
SE1	Site-specific landscape analysis to design nature-based solutions.
SE2	Good knowledge of the present status of agricultural soils to target region-specific soil threats.
SE3	Soil restoration: options and indicators for land degradation neutrality.
SE4	Soil biodiversity: status, and role in ecosystem services provided by soils.
SE5	Mitigate, adapt to, and restore soil salinization: understanding the process and enhance cropping systems with specific attention for irrigation under current and future climate conditions.
SE6	Soil futures: scenario modelling for assessing the potential of climate-smart sustainable soil management to provide multiple ecosystem services.
AD2	Tools for quantifying and communicating soil quality for healthy soils and healthy farms.
POL3	Support for soil and agro-ecological transitions across territories and agri-food chains for a circular bioeconomy.

4.6 Expected Impact 3 - Networking and knowledge sharing: Strengthening scientific cooperation at the European level including training young scientists

4.6.1 Introduction

Cooperation is needed not only between scientists but with society as a whole. The EJP SOIL aims to have an impact on how science contributes to mitigation and adaptation to climate change and sustainable production without damaging the environment or the livelihoods of farmers (Bouma, 2019a,b; Bouma *et al.*, 2019). Current soil science communities of practice (academics, policymakers, farmers and advisors, industry and agro-business) remain fragmented. Stakeholders point to the lack of communication among scientists, the lack of public awareness about soils, and the lack of science in practice and policy. Soil science education is also fragmented, which affects research capacity and international competitiveness in terms of research performance. Equally, it hampers the capacity of soil science contributions to common development policies such as Farm to Fork, the EU Green Deal, and the EU Water Framework Directive, where soil health and climate-smart soil management are core issues.

The third Expected Impact of the EJP SOIL is defined as "Strengthening scientific capacities and cooperation across Europe including training of young scientists", it is connected to the knowledge sharing section of the knowledge framework (Fig. 1). Following the format of the European Commission, cooperation within and outside the EJP SOIL is based on the concepts of dissemination and exploitation. To enable knowledge transfer and sharing, the EJP SOIL develops three activities, i) establishing networks for soil scientists, science-policy, and science-society comprising all end-users such as practitioners and investors in private and public sector; ii) awareness raising among stakeholders involved in academia, research, policymaking, and practice; and iii) capacity building of young soil scientists.

The EJP SOIL contributes to the main objectives defined in the EU Mission A Soil Deal for Europe report, which is to raise awareness about the importance of soils, engage with citizens, create knowledge, and develop solutions for restoring soil health and soil functions to benefit food provision, the environment, and people.

4.6.2 Identified knowledge gaps

The inventory of knowledge gaps across Europe shows that to date there are few comprehensive assessments of capacity building or network mapping for soil science, policy, and management. Most of the literature on implementation and uptake of best soil carbon management practices is focused on advisory services and farmers (e.g., Mills et al 2020; Ingram & Mills, 2018).The draft findings of the EJP SOIL Task 5.1 Survey of soil science in Higher Education in Europe (Villa Solis et al., 2021)[16] show that only 10% surveyed entities had a dedicated soil science department. Most soil science teaching at the tertiary level is embedded in a department where environmental sciences, agricultural sciences, or earth sciences are the main academic topics. Respondents reported an increased enrolment in BSc programmes and no change for MSc and PhD programmes. Mixed trends could be seen for specific countries and universities, with both increases and decreases in student enrolment. The draft findings also provide insights into internationalisation, the teaching of generic skills needed of a new cadre of soil experts, and perceptions of the job market for soil experts. To foster an enabling environment in which soil knowledge will be used in practice, it is crucial that actors are engaged in transdisciplinary cooperation for regular exchanges among and between companies, research institutes, intermediaries, customers, authorities, and financial organizations. To succeed, networks need to be created that will thrive beyond the EJP SOIL programme time frame.

Important questions:

- How can the EJP SOIL partners work together with regional stakeholders, policymakers, and national hubs to support the implementation of evidence-based policies on climate-smart sustainable agricultural soil management?
- How can the EJP SOIL research address the knowledge gaps that farmers, practitioners and policymakers face in multiple dimensions of soil management?
- How to build a community to exchange ideas and achieve progress on climate-smart sustainable management of agricultural soils between Member States through the implementation of climate, soil, and agriculture policies (CAP, SDGs, Farm to Fork Strategy etc.)?
- How to promote interaction with the private sector to reward sustainable agricultural soil management.
- What are the capacities needed in academic, research, policy, and farming and business areas to implement climate-smart sustainable management of agricultural soils?
- Which economic, social, and cultural barriers need to be shifted to make climate-smart agricultural soil management acceptable?

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[16] Conducted among 86 institutions in 25 EU countries.

4.6.3 Activities, and outputs to address Expected Impact

One EJP SOIL objective is to develop dedicated networks of researchers, policymakers, and practitioners sharing new knowledge (see knowledge sharing section of the knowledge framework in Fig. 1) and insights on the development and implementation of climate-smart agricultural soil management at farm, advisory, and policy levels. Toward that end, the EJP SOIL networking activities aim to include all stakeholders in Europe that have an interest in or an influence on agricultural soil management. These stakeholders include the farmers who are custodians of the soil and scientists working with soils as well as policymakers, civil society, practitioners, and representatives of the private sector. We have identified the following outputs to foster climate-smart sustainable management of agricultural soils.

- Science-science dialogue: soil scientists interacting within their discipline and with other disciplines such as agronomy, climatology, hydrology, social sciences, economics, and human health.
- Science-society dialogue: science-farmers as well as science-business interactions.
- Awareness raising among soil stakeholders and the general public.
- Science-policy dialogue: interactions on different levels in the policymaking process (local, national, regional, EU).
- Targeted training and network building of young scientists across Europe and for data harmonization (WP5, WP6).
- Training in digital environments, which are new opportunities.

Science-science network: Better aligned scientific communities in Europe and beyond

Despite the many conferences where scientists meet and exchange knowledge, boundaries remain between disciplines while solutions for current societal issues lie in interdisciplinary and transdisciplinary approaches. To build a better aligned scientific community, the following activities can be envisioned: i) create synergies across disciplines to facilitate cross-fertilization, which will streamline and harmonize current concepts and research methodologies so theoretical studies and applications of climate-smart sustainable soil management across Europe can be compared; ii) create an established and integrated network of soil scientists at the EU by the end of the EJP SOIL programme; iii) a strategic engagement between the EJP SOIL scientific community and the international community of soil science researchers that will ensure the EJP SOIL is well connected and contributes to global public goods during the programme and beyond (e.g., EUROSOIL, Wageningen Soil Conference, TERRAenVISION, AQUACONSOIL, Circular@WUR, EGU-SSS and global initiatives 4p1000, GSP and assessments; IPCC, IPBES).

Science-society networks: A multi-actor approach with farmers and the private sector

Several constraints have been identified in the EJP SOIL reports (D2.8) that restrict the transfer of knowledge between science and society. Dissemination is insufficient or does not convey useful information. Communication is not effective and not clear for all stakeholder categories and there is a lack of evidence-based policy and incentives for farmers and other end-users to address soil management for climate-smart sustainable agricultural production. Therefore, the

EJP SOIL is taking steps to foster dialogue between scientists and key stakeholders at EU, national and pilot local levels.

The EJP SOIL is taking action with three categories of partners outside academia and research i) broader science-society and citizen action, including representation of farmers, extension services, and agro-business related to the EJP SOIL, ii) policymakers and regulators in public service, and iii) pilot innovation spaces for research activities with farmers and agro-business representatives. The science-society interactions through webinars, conferences, discussion forums, citizen science projects, and topical consultations are what allow multi-actor conversations and facilitate the co-creation of new knowledge with non-academic stakeholders. This will encourage multi-sectoral collaboration, allowing practitioners and policymakers to develop joint understandings by sharing information and co-creating new knowledge. It will also lead to greater cross-fertilization of ideas to develop new methods and approaches for the effective implementation of soil management strategies. The EJP SOIL dialogues and engagements can also support evidence-based EU and national policy measures by facilitating access to new research and innovation outputs of the EJP SOIL partners by inviting key stakeholders to the national EJP SOIL platforms (National Hub meetings, webinars, workshops etc.). Stakeholder engagement is essential for the co-design of solutions that are sustainable from a biophysical point of view and also sustainable and acceptable for farmers from a technical and socio-economic point of view. The EJP SOIL partners are facilitating knowledge applications and supporting innovation by involving the private sector and farmers in research, dissemination and outreach activities through participation in field studies and project awareness raising, knowledge exchange, and educational events.

Awareness raising among stakeholders and the general public

The lack of awareness regarding the links between soil health, food and product quality and safety, and human health was flagged as a major issue in several reports (IPBES, IPCC, ECA, 2018, 2019). The EU Mission A Soil Deal for Europe in the area of soil health and food suggested activities and tools related to awareness raising such as: i) Living Labs (open research locations) and Lighthouses (places for demonstration); and, ii) communication and citizen engagement. The EJP SOIL will foster better awareness by i) developing instruments to encourage the active participation of stakeholders in project activities, such as topic consultations, national and EU policy forums, national and EU soil science days; ii) developing dissemination tools to inform the general public about soils through the online knowledge platform hosted by the EJP SOIL website; iii) target the whole agro-food chain (farmer, advisor, retail/processing industry, consumers, policy, research) to support farmers in sustainable soil management by aligning our communication, dissemination, and uptake strategies to each group and creating communication materials and publications; Iv) target citizens by involving them in research and setting up citizen science projects within the EJP SOIL projects whenever possible.

Science-policy

See chapter 4.5b of this document for outputs related to the need for better science-policy communication.

Strengthening the capacity of a new generation of soil scientists

The EJP SOIL survey (T5.1, M6) among 86 higher education institutions shows that the development of skills across education in soil science may need to be strengthened to prepare a new generation of soil science experts. The survey showed that traditional lecture-based teaching dominated soil science teaching and learning activities, both at BSc and MSc levels. At the BSc level, about one-third of all courses did not have any computer modelling component. However, results suggested that study programmes are evolving to include more general competencies and active learning methods (e.g., problem-based learning, case studies). Nonetheless, the results indicate a need to better understand what soil science programmes across European schools are teaching and how teaching is delivered. The EJP SOIL activities will strengthen European soil science networking among PhD and junior-senior researchers across Europe and enhance excellence in research by developing PhD and topic courses and by involving learners in research project activities and knowledge exchange meetings organized.

Activities needed in WP Tasks

Based on the gaps identified, we defined three categories of activities: i) network building; ii) awareness raising, and iii) capacity building.

Network building: knowledge sharing between and among scientists, and policy makers and practitioners

1. **National hub workshops:** These are national stakeholder groups representing researchers, practitioners, and other interested stakeholders to share information and inform the EJP SOIL with national information and concerns. The national hubs help ensure that national activities are coordinated and serve to inform the direction and activities of the EJP SOIL. As questions arise, they will be addressed during these workshops by focusing on knowledge and data gaps and Member State specificities and barriers to adoption of sustainable soil management (WP 2).
2. Dedicated **research projects on awareness raising and educational workshops** that will focus on specific topics to provide information and address the knowledge needs of stakeholders.
3. **Annual General Assembly and Annual Science Days (WP1, WP9).** Open to all partner institutions, these meetings are an opportunity for stakeholders to report and discuss the EJP SOIL progress as a whole as well as the results of the individual research projects. They also provide an opportunity to meet colleagues, network, and discuss the most relevant scientific topics in formal (Annual Science Days) and informal events (dinner and lunch receptions). In the mid-term (year 3) and final meeting of the EJP SOIL, an additional meeting will be held for all interested stakeholders (scientists, public relations, media, policy makers, land managers, etc.) to update them on the EJP SOIL progress and receive their feedback.
4. Inventory of soil related projects and initiatives in and outside Europe (WP7) to know which other networks the EJP SOIL should connect to.
5. **Strengthen the European soil science community** through institutional networks for infrastructure and knowledge exchange through project collaborations and staff exchanges (T 5.4 and 7.4)

6. **Explore new web-based opportunities** that we have come to know because of COVID-19 for networking and capacity building such as webinar and MOOCs.

Awareness raising: knowledge sharing between soil scientists and other non-soil science scientist, practitioners, policy makers and the general public.

7. **Awareness raising activities**: promotion of knowledge through the EJP SOIL website, newsletter, online knowledge platform, EJP SOIL publications, news articles, public lectures, topical interviews, participation in the soil webinars, seminars, conferences, open round tables and consultations, posts on social media, policy briefs, dissemination of activities by the EJP SOIL partners, and research project participants in national media.

Capacity building: knowledge sharing between senior and junior scientists

8. **Intra- European doctoral programmes** (WP5) to support young scientists training and networking on climate-smart agricultural soil management, including the use of open geodatabases and new tools for agricultural soil management (WP6).
9. **Support funding for research exchanges and visiting researchers** (WP5). This includes lecturers to enhance network capacity across joint activities and partners engaged in the EJP SOIL. It also includes the possibility to visit long-term research sites and soil laboratories (WP7) to promote Living Labs by launching calls for visiting scientist grants to facilitate cooperation among researchers across Europe.
10. Training in data management and addressing needs for capacity in SOC data reporting (WP5).
11. **Develop training for scientists** on effective dissemination and communication to non-scientific stakeholders (WP5/WP8/WP9).

For further implementation of networking and capacity building, see sections 4.8, 4.9 and chapter 5 of this document.

Table 6: List of topics for Networking and knowledge sharing (See Annex 2 for a description of topics)

List of topics for Networking and knowledge sharing	
NET1	Citizen science (including farmers) protocols to support science-based soil knowledge and site-specific policy applications.
AD1	Regional Living Labs and Lighthouses for healthy soils and sustainable farms.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 862695

4.7 Expected impact 4 – Supporting harmonized European soil information, including international reporting.

4.7.1 Introduction

To ensure European soils continue to fulfil their function and prevent their degradation, there are needs for soil monitoring, including state indicators (soils properties), impact indicators (soil quality, ecosystem services), and drivers indicators (soil management). Europe is relatively rich in terms of soil data (state indicators) due to regional, national, and EU initiatives. However, information is collected using different methodologies, dispersed in different countries, and often unavailable to the public. Serious knowledge gaps still exist, for example, on the characteristics of soils in various regions of Europe, their fertility and capacity to store carbon, and their degradation status.

Transboundary research is often hampered due to the lack of standardization, either in the method used for collecting and storing soils and data or in the methods used to develop soil indicators. Currently, the only maps without boundary issues are based on a single European survey programme (LUCAS) that suffers several limitations such as low resolution and sampling strategies. To advance agricultural research and international reporting, up-to-date and transboundary soil information is required to develop common references that allow for better-informed strategic decision-making and science support, and policy and implementation challenges at multiple scales. There is thus a need for, i) an integrated framework for data exchange and harmonization in Europe; ii) up-to-date transboundary soil information that allows for strategic decision-making and science support, and policy and implementation issues at multiple scales; iii) development of shared impacts and driver indicators for European soils.

4.7.2 State-of-the-art on data harmonization

There is a wide range of existing information on soil properties and state indicators, obtained from both monitoring and single sampling campaigns. These data are in the form of databases or geodatabases (GIS). The best captured soil parameters are carbon concentrations in soils and their changes over time, macronutrient (N, P, K) and micronutrient (Cu, Mn) content in soils, cation exchange capacity and base saturation of soils, soil texture, and contamination with potentially toxic elements especially Cd, Co, Cr, Cu, Ni, Pb and Zn (T2.4.2); Arrouays *et al.*, 2020).

It is difficult to compare soil property information from different countries because different methodologies were used to collect and assess data. Notably, there is a large variation in sampling depth and soil bulk density is often missing and estimated through pedotransfer functions from other measured soil parameters. A standard protocol is still missing (e.g., (T2.4). At the global level, this is currently in development by the Global Soil Partnership (GSP) through the Global Soil Laboratory Network (GLOSOLAN) for standardized lab procedures and through building a distributed global soil information infrastructure (GLOSIS) that aims to bring together and at some point harmonize soil data exchange. Europe passed the INSPIRE directive, providing binding standards for sharing soil information but there are technical impediments to implementation. In addition, data holders want to maintain ownership. This must be resolved through an overview of the current policies and the creation of a common data policy. The technical challenges require defining a data harmonization procedure.

Recently, several attempts have been made to assess the contribution of soil to the provision of ecosystem services (Bunemann *et al.*, 2018; Debeljak *et al.*, 2019; Fossey *et al.*, 2020; Lehmann *et al.*, 2020; Schwilch *et al.*, 2016, 2018) and report on soil degradation processes (Veerman *et al.*, 2020) identified as soil threats in the European Soil Thematic Strategy (Cowie *et al.*, 2018; Prăvălie *et al.*, 2021; EC, 2006; 2012; Stolte et al, 2016) and as Land Degradation Neutrality for the UNCCD. However, different concepts and indicators are implemented across countries (e.g., soil quality, soil health) to assess the multifunctional state of soils. Therefore, indicators based on soil properties have to be developed and shared, and common reference and threshold values need to be set for the diversity of soil types and land uses at the European scale. Research is also needed on modelling soil functions and soil threats for mapping.

Reporting and monitoring soil conditions and functions is often hampered by the scarcity of funds and different strategies, and because traditional monitoring methods are time-consuming. Soil spectroscopy has been developing in the last years as a promising technology to speed up and reduce the cost of soil surveying. Several proximal sensing techniques have also been studied which would make it possible to cost-effectively enlarge the monitored datasets. These include γ-rays, X-rays, ultraviolet, visible, and infrared reflectance spectroscopy, laser-induced breakdown spectroscopy, microwaves, radio waves, magnetic, gravimetric, and seismic sensors, contact electrodes (Rossel *et al.,* 2011). Harmonization of spectral measurements and calibration database libraries and procedures to derive soil parameters from soil spectra is strongly needed to fully validate these techniques and allow them to function to their full potential. Currently, two global initiatives are addressing this issue, the GLOSOLAN Soil Spectroscopy Working Group and the IEEE P40005. These techniques would also allow for mapping soil management (driver indicators).

4.7.3 Identified knowledge gaps

Lack of existing soil data and data sharing: An agreed data sharing policy is the key to advancing the quality of soil information in Europe. In term of state indicators, many countries lack soil information on soil carbon stocks, qualitative characteristics of organic matter, soil water retention potential, contamination with organic pollutants, biological parameters, and bulk density (D2.2: Stocktaking on soil quality indicators and associated decision support tools, including ICT tools). Soil data are common for surface soil layer but less common for the entire soil profile and absent in some countries. Data is also lacking for soil management at the field scale and access to data is limited.

Lack of data harmonization and standardization: Soil monitoring initiatives have been implemented in many countries but most rely on private or regional initiatives with no standardization and without much national or international coordination (D2.7). Most participating countries use the national soil classification systems claiming that either the World Reference Base (WRB) classification to describe local soils is inadequate, or acknowledging the insufficient formation to the WRB of the people in charge of the soil monitoring services in the different countries (D2.2). There is a lack of consensus on the methods for sampling and measuring soil characteristics in terms of soil organic carbon stock estimation and soil biodiversity assessment (D2.7).

Lack of soil quality and health indicators (impact indicators) and mapping strategy: Despite several recent projects having worked on indicators and monitoring plans[17] there is no consensus on a set of indicators, baselines, thresholds, or targets. Therefore, definitions are badly needed along with detailed monitoring plans. These gaps prevent model development, mapping, and effective assessment of policy interventions.

Lack of knowledge on the potential of remote and proximal sensing for soil monitoring: There is still a lack of coordinated research to make these techniques sufficiently reliable to be integrated into soil monitoring strategies. Although some sensing techniques are well researched and developed, others are less so. The different soil properties that could be estimated through proximal and remote sensing also need investigation, including more soil properties (state indicators), soil management (driver indicators) and possibly soil physical and biological functions (impact indicators).

Applying workflow towards soil data harmonization and sharing for each country

Soil data harmonization, storing, and exchange is the main element of the knowledge development done in WP6. Based on the common definitions (code lists and vocabularies), the workflow and necessary tools provided by WP6 and INSPIRE require that countries harmonize or map their national data to international standards for exchange and open web links to the common distributed soil information systems that will be developed for an agreed common data policy. The expected output is that partner countries will become compliant with INSPIRE Soil and allow connections to GLOSIS.

4.7.4 Activities, and outputs to address this Expected Impact.

Outputs and activities needed to reach this impact are embedded in several of the compartments of the knowledge framework (Fig.1). Knowledge harmonization of measurements, monitoring and storage is the main objective of this Expected Impact (4). However, this work is fed by new knowledge on measurement techniques; and will provide tools for the implementation of climate smart sustainable soil management (knowledge sharing and application) by policy makers and end-users. This flow between the knowledge framework compartments is needed to enable the transition that is in front of us. The outputs and activities identified are:

Existing soil data and data sharing:

1. Stocktaking of national and EU soil management data and auxiliary data available and of mapping procedures;
2. Stocktaking of national soil and EU monitoring systems and protocols for monitoring;
3. Stocktaking of European and national legislation on soil data sharing;
4. Compiling a proposal for common soil data sharing policy;
5. Developing an easy-to-update distributed soil information system, linking the sharable national data of EU members according to INSPIRE and allow querying through a portal.

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[17] E.g., RECARE and SoilCare. See the review on soil quality by Bunemann et al, 2018.

Data harmonization and standardization:

1. In collaboration with JRC/ESDAC, DG-ENV, ETC, Pillar5-GSP:
    a. Compile international and national code lists and vocabularies for INSPIRE;
    b. Resolve impediments in implementation of INSPIRE;
    c. Help to provide workflow for implementation of INSPIRE, mapping of (national) databases and data sharing;
    d. Provide or help provide a mapping between INSPIRE and GLOSIS.
    e. Comparative analysis and harmonization of soil data analysed with different (ISO) standards.”
2. Elaboration of a common proposal for improvement of the LUCAS soil monitoring campaign after deep analysis of the limitations of the existing database, in accordance with national monitoring programs, as a first step to the establishment of an European Soil Observatory, with INSPIRE compliant harmonized procedures.

Soil quality / health indicators and mapping strategy:

1. Stocktaking of indicators for assessing soil quality, soil functioning and ecosystem services in link with call ES1/ES2;
2. Research on modelling soil functions and soil threats for mapping. Defining threshold values (in collaboration with JRC/ESDAC, DG-ENV, ETC and call ES1/ES2);
3. Co-develop soil impact indicators;
4. Defining common procedures for soil mapping (baseline properties (state indicators) including soil biodiversity and selected soil impact indicators);
5. Delivering thematic soil geodatabase and maps at 1km resolution of soil properties, soil functional properties, including carbon, soil degradation rate and fertility.

Potential of remote and proximal sensing for soil monitoring:

1. Protocol for sound implementation of these techniques for soil monitoring purposes.
2. Research on monitoring through remote/proximal sensing;
3. Research on mapping soil management (drivers indicators) through remote sensing;
4. Stocktaking of national and EU mapped data of soil management (in collaboration with JRC/ESDAC);
5. Compiling the research to derive a protocol for sound implementation of these techniques for several soil properties/indicators.

Table 7: List of topics for Harmonising (see Annex 2 for a description of topics).

List of topics for Harmonising	
MT1	Good knowledge of the present status of agricultural soils: Innovative techniques for soil mapping and assessing spatial and temporal variation of soil properties (1st call).
DATA 1	Innovative techniques to monitor SOC stocks and soil degradation and restoration changes in the EU, using spectral systems, NIRS/MIRS, and other proximal sensing tools.
DATA 2	Feasibility of mapping of soil management practices through remote sensing.
DATA 3	Estimation of soil physical degradation through remote and proximal sensing.
DATA 4	Comparative analysis and harmonization of soil data analysed with different ISO standards.
ES1/ES2	Methodologies and tools to assess the contribution of soils to ecosystem services for assessing soil quality (1st call).

INDICATORS 1	Modelling soil OC, mapping soil quality, soil functioning, and ecosystem services.
INDICATORS 2	European soil biodiversity forecast: biodiversity indicator stocktaking, development, modelling and mapping.

4.8 Expected Impact 5a: Adoption of sustainable soil management, fostering the uptake of soil management practices which are conductive to climate change adaptation and mitigation for end-users.

4.8.1 Introduction

In the long term, the EJP SOIL aims to promote farmers to be and to be seen as the stewards of land and soil resources. Both farmers and society face many challenges related to agricultural soils. To overcome these challenges, farmers need to be able to implement sustainable soil management strategies as part of their overall farm management strategies.

The societal challenges connected to agricultural soil management require systemic change and a paradigm shift. Rather than implementing ad hoc measures, an integrated approach is needed that treats farming systems in the context of the surrounding social, economic, and political environment (Caron *et al.*, 2014; Bopp *et al.*, 2019). The transition process towards sustainable soil management depends on many factors. Innovation in the agricultural sector takes many forms, hence, a wide range of transition pathways. The transition literature shows the need for developing new strategies and phasing out the old unsustainable systems (Loorbach *et al.*, Visser *et al.*, 2019). Despite several attempts to explain the adoption of sustainable agriculture measures, a consensus on the drivers or a strategy is lacking (Kollmuss and Agyemann, 2002; Pilarova *et al.*, 2018). The past has taught us that the linear model of science and policies prescribing measures does not foster sustainable soil management. Instead, co-innovation and co-design with farmers are needed to develop new sustainable strategies and adapt current strategies to local situations. This means that farmers should recognize the challenges associated with their soils and be able to assess the costs, benefits, side-effects, and the potential of new management strategies and practices. It is not often clear what boundary conditions are needed for farmers to make a change in their management practices (Cerdà *et al.*, 2018; de Rooij *et al.*, 2021). This means that researchers and advisers must learn to recognize how the adoption of new practices and systemic transitions impact the way farmers relate to their soils and how they make sense of their job within local and political networks of relations and shared representations (Toffolini *et al.*, 2017). Management options that show clear benefits and may be relatively easy to apply tend to get adopted quickly (Verstand *et al.*, 2019). Whether such options make sense in a broader cultural, social, and political context of farming and soil understandings also deserves scrutiny.

4.8.2 State-of-the-art on the adoption of sustainable soil management practices

Current status of adoption of sustainable management practices

The level of implementation of sustainable soil management in Europe varies substantially among farmers. The current status of the most promising management practices was analysed in relation to their level of uptake in research, policy, and farmers' practice. Although quantitative information on the current scope of adoption is missing, it is estimated that the

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adoption of management practices directly related to production increase and management options included in the CAP are not widespread and uptake of measures focusing solely on soil quality and the environment are limited.

From D2.1 (Synthesis of the impact of sustainable soil management practices in Europe), several sustainable management practices were found promising. Some useful soil tillage and cover management strategies identified were: non-inversion, reduced tillage, no till, and direct seeding. Successful crop and cropping systems were noted, specifically crop rotations and cover and catch crops and using grasslands and pasture with legumes and perennial crops. For nutrient management and crop protection, the most frequent practices mentioned were organic fertilizers, efficient fertilization, "use of soil amendments, and biofertilizers. In water management, the most often reported were drainage systems, efficient irrigation, and improving water storage capacity. To date, there are different levels of adoption of these strategies in different parts of Europe.

Barriers in the adoption of sustainable management practices (D2.8)

Whether farmers adopt a sustainable management practice, both in environmental, social and financial terms, depends on many factors (Zhang *et al.*, 2018). Several enabling conditions and barriers have been analysed. An important barrier is the uncertainty of the impacts of potential practices on soil quality and farm profits (Hvarregaard Thorsøe, 2019; Cerda *et al.*, 2017). The decision-making process is complicated by trade-offs, for example, between environmental and economic benefits, short- and long-term benefits, and between different soil quality aspects. Barriers are largely dependent on the kind of management practice in play.

Other important barriers are the lack of appropriate policies and incentives (see chapter 4.9 on Expected Impact 5b), the application of knowledge, technological constraints, and socio-economic factors. To understand the adoption of sustainable practices, more attention must be given to how sustainable soil management practices are embedded within the broader social construction of agricultural identities and practices in relation to advisers, agricultural union groups, chemical companies, and other farmers. To achieve this goal, communication with end-users is essential. However, there are too few knowledge brokers to facilitate the flow of knowledge and knowledge needs between science and society, which inhibits co-creation and co-innovation (D2.7) to mitigate the lack of basic agricultural soil knowledge such as soil physics, soil diseases, and fertilization practices.

Knowledge availability and application (D2.6 and D2.7)

There is ample soil science research (D2.7: Report on the current availability and use of soil knowledge) but knowledge is fragmented, difficult to access, and does not reach farmers easily in a useful format. Other challenges arise because the knowledge produced by universities needs to be translated to the local context of farmers. Advisory services are an important intermediary mechanism to help with this translation, however, the capacity of organizations and the quality and focus of farm advisory services vary within Europe. This partly explains the differences in engagement to sustainable soil management in European countries.

Technological constraints

The availability of technology is often mentioned as a barrier. Many technological innovations for sustainable soil management practices are developed (i.e. precision agriculture, affordable machinery for non-tilled seedbeds). However, these innovations need to fit the farmer's context and meet their needs.

Socio-economic factors

Socio-economic factors are key to the successful implementation of long-term measures (D2.3: Synthesis on estimates of achievable soil carbon sequestration on agricultural land). A farmer's income determines their ability to make investments in innovations, or the ability to switch to less intensive management practices. Farmers' perceptions and beliefs were found to play a key role in explaining the level of adoption (Mitter and Schmidt et al., 2019). The motivation of farmers to adopt sustainable management is influenced by the behaviour of other farmers and the opinions of intermediaries such as advisers and suppliers. There is a need for information about the feasibility of agricultural measures, including their economic efficiency and social acceptability (D2.3: Synthesis on estimates of achievable soil carbon sequestration on agricultural land). Consideration of a realistic area where measures can be implemented is often not taken into account in research (D2.3). Generic measures are not necessarily useful or sustainable in all cases and need context, for example, the spatial separation of livestock and arable and fruit production, limiting organic fertilization rates in certain regions (D2.1: Synthesis of the impact of sustainable soil management practices in Europe).

4.8.3 Identified Knowledge gaps

Given the diversity of agro-food systems, there is no one-size-fits-all solution and a variety of new approaches will be needed to achieve sustainability. Rather than push the implementation of research findings, the challenge is to account for diversity and provide knowledge that may lead to sustainability transition pathways. It is crucial that the right actors are brought into a transdisciplinary cooperative dialogue enabling regular exchanges. A bottom-up approach is preferred over a top-down approach by some stakeholders. In a bottom-up approach, farmers' meanings, relations, research needs, contexts, and practical considerations must be considered while generating knowledge that will be the basis for further knowledge development. Other stakeholders suggest a combination with top-down approaches also to steer the transition towards new types of systems such as circular agriculture.

Outputs needed to reach this impact

One key to fostering sustainable soil management is generating situated and context-dependent assessments of the challenges farmers face and to account for the diversity in the agricultural sector, also including social and cultural challenges regarding soil conceptions and professional identities. Regionally based co-innovation processes and bottom-up accounts for the diversity of practices will foster sustainable soil management. Research on effective incentives for the adoption of new management strategies is essential (Prager *et al.*, 2011; Marcos-Martinez *et al.*, 2017; Hessel, 2018; Cerdà *et al.*, 2018). This process involves strengthened networks, especially regional joint research networks involving the research community and the farming sector. The research community provides fundamental knowledge regarding soil processes and generic knowledge related to management strategies, supplemented by the practical experience-based knowledge of local stakeholders. Other stakeholders such as farm advisers, contract workers, suppliers and buyers need to be involved to enable systematic changes. Together, they will be able to experiment with and develop solutions for short- and long-term societal challenges.

Regional long-term field experiments are needed to test and assess ideas, providing quantified information about the economic, environmental and practical consequences of management strategies in the regional context. Based on the available knowledge and regional field experiments, specific guidelines and tools can be developed. Greater involvement of stakeholders in the organization of research provides a regional knowledge sharing structure, supporting lifelong farmer-to-farmer learning. These field experiments should be complemented with demonstration activities at commercial Lighthouse Farms that serve as showcases in their communities. Indeed, farmers who are likely to teach or inspire other farmers have greater legitimacy and can represent the reality their colleagues experience (D2.7).

4.8.4 Activities, and outputs to address this Expected Impact

Outputs and activities needed to enable the transition towards a climate smart sustainable agro-ecosystem in which soil management plays a key role is embedded in several of the compartments of the knowledge framework (Fig.1). This impact mainly relates to knowledge application, but to be able to improve the implementation of knowledge, the right knowledge needs to be asked for by policy makers and end-users (knowledge development); and the information needs to be brought to the people that need it efficiently and effectively (knowledge transfer). The flow between the knowledge framework compartments is essential to enable end-users to adapt to climate change while ensuring a good livelihood for them. The outputs and activities identified will be addressed in WPs tasks and calls topics listed in Table 8.

1. A stocktaking of current experiences related to knowledge transfer and co-innovation processes in European countries to provide insights into their effectiveness and offer valuable lessons. Special attention needs to be given to embedding co-innovation within existing knowledge development frameworks (WP5).
2. A stocktaking and synthesis of projects dealing with best practices and guidelines for farmers and advisers to foster adoption of sustainable soil management practices across European countries to be shared and adapted to other countries and regions (WP7/9).
3. Communication tools targeted at specific audiences (WP8/9).
4. Develop stakeholder specific plans for the use and dissemination of results of all the EJP SOIL projects (WP3/WP9) and collaborate with running initiatives that focus on adoption of climate smart sustainable agricultural soil management[18].

Table 8: List of topics for Adoption of sustainable soil management (see Annex 2 for a description of topics).

Topics for Adoption of sustainable soil management	
AD1	Regional Living Labs and Lighthouses for healthy soils and sustainable farms.
AD2	Tools for evaluating and communicating soil quality for healthy soils and sustainable farms.

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[18] https://www.eragas.eu/en/eragas.htm

AD3	Soil-specific guidelines and decision support tools with a focus on water storage, soil organic matter, and nutrient use efficiency.
POL3	Support for soil and agro-ecological transitions across territories and agri-food chains for a circular bioeconomy.
NET1	Citizen science (including farmers) protocols to support science-based soil knowledge and site-specific policy applications.

4.9 Expected Impact 5b: **Science-policy** interface. Fostering uptake of soil management practices conducive to climate change adaptation and mitigation for the science-policy interface

4.9.1 Introduction

Soil is fundamental for ecosystem functioning and human activities (Keesstra *et al.*, 2016) and is as much a part of the natural environment as air and water. However, there is no direct policy at the EU level dedicated to soil protection or enhancing the capacity of soil to provide functions for primary productivity, nutrient cycling, water purification and regulation, climate regulation and C sequestration, habitat for biodiversity, and biological processes. Many existing EU policy instruments relate indirectly to soil protection and health (Vrebos *et al.*, 2017) as do several emerging agri-environmental policies (EU CAP, EU Green Deal, Farm to Fork strategy).

The EU Mission A Soil Deal for Europe has the protection and enhancement of soil health as a central goal. Across the EU and globally, there is an increasing awareness of climate change and its impacts. Growing concerns about soil health, carbon sequestration, and climate change mitigation are compelling governments to develop policies to protect citizen health and livelihoods and their natural environment and resources. Healthy soils, in direct line with human health and ecosystem health, is becoming a more important topic for policymakers.

Improved harmonization and implementation of soil policy are needed to enhance soil capacity to perform a range of functions and to meet soil health and climate change mitigation and adaptation targets. However, general awareness of the challenges affecting soil resources, e.g. erosion, compaction, soil fertility, salinization etc., and the role of soils in regulating our climate is low and hence, soils are often under-valued and given a low priority. Holistic soil health is often poorly considered. Nonetheless, people with a stake in agricultural soil management and governance across the EU Member States ranked maintaining and increasing soil organic matter, enhancing soil nutrient retention, avoiding GHG emissions, and enhancing soil biodiversity amongst their top priorities (D2.1: Synthesis of the impact of sustainable soil management practices in Europe).

To improve policy cohesiveness regarding climate, soil protection, and health, and to bridge knowledge gaps and enable policy stakeholders to develop, implement, and monitor future agricultural soil policies, there is the need to, i) identify synergies and trade-offs between existing policies across different scales to enable strategic policy decision-making and support the selection of integrated and cross-cutting soil protection measures and management practices; ii) to support scientific knowledge sharing with policy stakeholders and develop new frameworks for future soil policy and eco-scheme development, and for carbon accounting initiatives; ii) provide suitable tools, indicators, and indexes to enable better policy implementation and monitoring at multiple scales; and iv) to promote a better knowledge of soils among society, particularly farmers as custodians of agricultural soil resources and people involved in horticultural and floricultural activities in urban areas.

4.9.2 Identified knowledge gaps

An analysis of stakeholders across EU Member States found that existing policies are inadequate to tackle soil challenges. Stakeholders indicate that the gaps between the current realization of soil challenges and policy targets are large and that current policies are not future proof as they do not account for the implications of climate change on soils (D2.5: Report on identified regional, national and European aspirations on soil services and soil functions). There is a need to raise awareness among policymakers concerning sustainable soil management and soil degradation. Furthermore, there is a need to improve communication of scientific results and translate findings into a language that is understandable to policymakers, and that policy address concerns in ongoing processes. Across governments, soil policies tend to be siloed.

Efforts to coordinate policy development are challenging and often soil policies tend to lack a comprehensive vision. Stakeholders stress that current soil research initiatives are fragmented across disciplines and research activities and policymaking needs to be coordinated (D2.6: Set of reports on State of knowledge in agricultural soil management and D2.7: Report on the current availability and use of soil knowledge). There is also an increasing need for policies that offer solutions to multiple challenges. A more integrated approach is required, especially with regards to soil management in emerging and future policies such as the new EU CAP. This implies on the one hand that clear targets and indicators in policies and funding for more integrated and long-term research activities are common. In most EU countries, policies affecting soils and their management are scattered amongst many laws and regulations (e.g., agricultural, environment, climate, nature, spatial planning) and an integrated approach or soil policy framework with holistic vision is missing (D2.5: Report on identified regional, national and European aspirations on soil services and soil functions). This creates complexity and inconsistency and some policies are contradictory.

Stakeholders report an insufficient focus on elements that are important for ongoing policymaking for soils within current soil research. These include perspectives regarding the loss of soil organic matter and carbon sequestration, exploring the effects of climate change and mitigation, and preventive measures. This is also the case with soil health and its effect on food quality and human health. A range of measures and incentives are required with public and private funding. However, it is important to ensure the design and effective implementation of mechanisms are balanced with equitable and targeted use.

Inadequate monitoring was reported across most environmental zones, where much soil monitoring relies on uncoordinated private or regional initiatives and monitoring standards are poorly coordinated across regions (D2.6: Set of reports on State of knowledge in agricultural soil management and D2.7: Report on the current availability and use of soil knowledge). Monitoring systems often lack operational definitions of indicators, baselines, thresholds, targets, protocols, and detailed monitoring plans. This prevents model development and effective assessment of policy interventions. Generally, regional, soil, farm and field information is lacking. This makes it difficult for policymakers to assess the usefulness of the information they receive.

Stakeholders suggest that future policy objectives should take a region- or farm-specific approach, rather than general umbrella regulations that offer all farmers the same initiative, independent of the environmental context in their region, catchment, or farm. Stakeholders require clear policy targets while also giving farmers an opportunity to set their own goals for achieving these targets in consultation with local and regional governmental organizations. This would further enable customization and focus areas. Financial support is an important instrument to encourage farmers to sustainably manage their soils. Payments for ecosystem services, with special attention to payments for soil carbon sequestration, has been suggested by several Member States. Stakeholders stress that any certification and accounting methods must be practical to implement, accurate, and cost-effective.

4.9.3 Activities, and outputs to address this Expected Impact

A set of outputs and activities (including topics for calls, Table 9) have been identified that are needed to reach the Expected Impact related to enabling the transition towards a climate smart, sustainable agro-ecosystem with regards to the conditions needed from the policy site. Most of the work needed lies withing the knowledge application compartment of the knowledge framework (Fig. 1). However, equally important is the way the new knowledge is communicated (knowledge transfer) for the policy makers to be able to use it efficiently. The knowledge needs from the policy makers lie both in the knowledge development as well as in the knowledge harmonization compartment. The flow between the knowledge framework compartments is essential to enable policy makers to design policies that will enable the agro-ecological sector to make the transition needed for a more sustainable society.

The outputs and activities identified are:

A science-policy dialogue guided by WP8 will be initiated in some partner countries. The aim is to identify barriers policymakers encounter as they try to develop effective policies and identify research needs such as science-based knowledge and information, accurate and cost-effective monitoring systems, and farmer-citizen initiatives to enhance approaches to soil management at the regional and farm level. Citizen science can also contribute to closing the gap between national, regional, and local monitoring and policy requirements and help achieve better policy development. Following the identification of barriers and needs, further science-policy dialogue is needed to explore ways to overcome these barriers and lead to a science-policy roadmap. Existing data sources and the potential of innovative techniques for mapping soil health linked to soil management should be explored. Policy dialogues should also explore barriers and potential pathways a more holistic soil policy framework that bridges policy sectors such as agriculture, environment, and land use spatial planning.

Documenting and disseminating best practices regarding the use of the Rural Development Programme and eco-schemes under the CAP to promote sustainable soil management. This includes the development and documentation of indicators for soil quality and using incentives for the adoption of sustainable soil management, such as performance-based payments.

Developing tools and models for integrated policy support on a strategic level combining multiple soil challenges and measures. For example, agroecosystem models coupling soil, cropping systems, climate, and economic dimensions can be considered. Decision support systems should provide an understanding of the systemic effects of introducing new measures and take into account the costs and benefits of interventions.

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Sustaining innovation of agro-food production at national and European level through developing agroecology based on soil biodiversity functions, and using sensors and digitally-based decision support systems for optimizing the use of resources in spatially targeted and site-specific management. Such innovations are becoming central to sustainable soil management. They enable diverse production systems that produce a range of outputs at different scales. Digital technologies may be used as a lever for sustainable soil management as data management and modelling systems will allow for scaling up sustainable soil management across spatial scales. But supporting policies are needed.

National reports indicate a need to improve site-specificity (from a few km² to a few hundred km²) of knowledge available for policymaking to ensure targeting policy interventions (D2.7). This is a key element in agro-ecological transition processes. It could be facilitated by improving monitoring and ensuring that knowledge is available for policymakers using online decision support tools, and smartphone apps.

There are also unexplored opportunities with citizen science projects and for co-creation by farmers and scientists in real-life situations to improve the availability of soil data for policymaking. In the context of science-practice-policy interfaces, governance and the coordination of Living Labs with policy levels for research uptake and implementing solutions need to be addressed.

It is important to improve the overview, availability, and accessibility of soil data for stakeholders, including policymakers. This could be ensured by preparing a continuous collection of activity data, providing access for relevant groups of stakeholders, and developing white papers synthesizing state-of-the-art research. It is important to standardize soil monitoring programmes beyond countries to ensure comparability and ensure that documentation of measures can be used beyond a national context.

Table 9: List of topics for Science-policy interface (see Annex 2 for a description of topics).

Topics for Science-policy interface	
ES7	Enabling conditions to implement improved management options and tools to monitor soil quality: analysis on how soil indicators could be used to support CAP measures.
POL1	Increasing soil protection and soil health within public policy.
POL2	Enabling conditions for enhancing climate-smart and sustainable soil policy: schemes for payment for ecosystem services including soil carbon sequestration.
POL3	Support for soil and agro-ecological transitions across territories and agri-food chains for a circular bioeconomy.
POL4	New social and economic methods and scenarios for policy development.
POL5	Tools and models for supporting integrated soil policy.
NET1	Citizen science (including farmers) protocols to support science-based soil knowledge and site-specific policy applications.
INDICATORS 1	Modelling soil functions and soil threats for mapping soil quality, soil functioning, and ecosystem services.

5. The EJP SOIL as a programme: Approach to research activities and knowledge interaction with all stakeholders

The chapter outlines the rationale behind the approach of the EJP SOIL research activities with specific attention to research projects within the programme. The research projects in EJP SOIL are not stand-alone. The EJP SOIL research projects need to be organised to facilitate alignment and integration of all EJP SOIL research activities with, i) EJP SOIL impact pathways ; ii) other EJP SOIL activities; iii) the knowledge framework; and iv) EJP SOIL stakeholders (Figure 6).

In Figure 6, each research project is i) linked to one or more knowledge compartment; (ii) will interact with other EJP SOIL projects; iii) strives to integrate sections of the knowledge framework as part of their workplan, even though each project may have its main focus in one knowledge framework compartment, the other three should be addressed when relevant; and iv) has a link to soil stakeholders. This workflow will be ensured through a set of project requirements and the provision of management tools provided through internal and external calls.

Integration within the EJP SOIL

The partners of the EJP SOIL form a network of soil scientists all over Europe that facilitates research integration. Each research project consists of partners across Europe aiming for a geographical balance. In addition, a network of long-term experimental sites and laboratories is developed, facilitating the exchange of data and experience within partner and outside institutions and welcoming scientists from across Europe. The EJP SOIL has multiple calls for visiting scientists to enable collaboration between partners for both junior and senior scientists.

Integration of knowledge to address research domains

The EJP SOIL work package activities and research projects are aligned to Expected Impacts and research domains as described in Chapter 3. These domains are linked and are not approached individually. To assure progress towards specific research domains and timely insights, all projects and work packages inform the consortium about their progress within the annual work programmes and progress reports. The workplans of the work packages and research projects address this interaction in more detail. The EJP SOIL has developed a set of tools to facilitate interaction: i) the general assembly and associated annual science days; ii) the website and internal collaborative platform (SharePoint), iii) the EJP SOIL newsletter and iv) networking events. Partners are encouraged to actively seek collaborations with the EJP SOIL research projects.

Contribution to the knowledge framework

EJP SOIL works within a framework for knowledge management (see section 2.1). Each EJP SOIL project has a focus on one part of the knowledge framework but needs to ensure that newly generated knowledge flows to the other parts, either within the project or through other EJP SOIL activities.

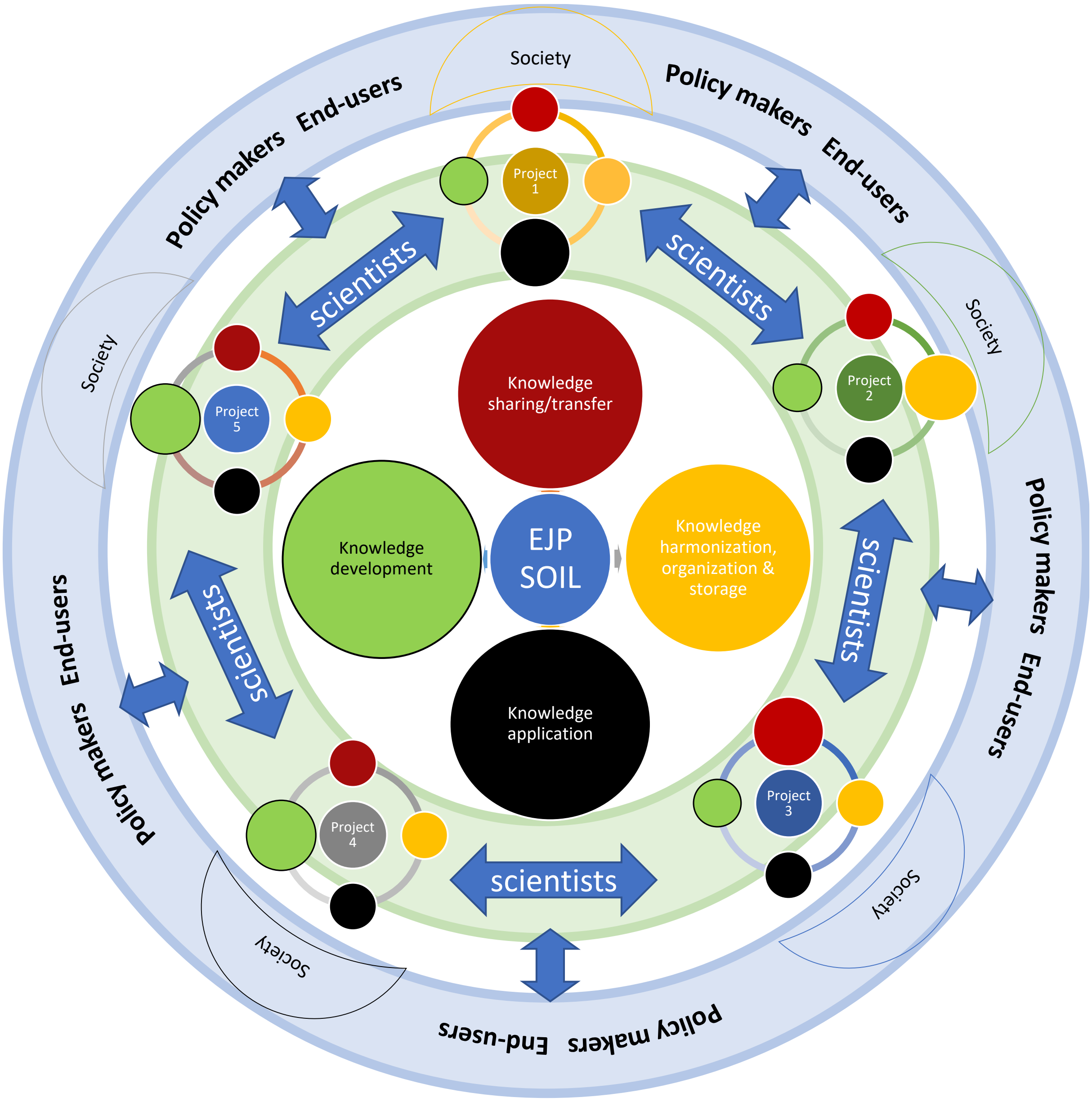

Figure 6: Alignment of knowledge management and stakeholder interaction in research project in the EJP SOIL. Inner circle: research takes into account all elements of the knowledge framework; green circle: the EJP SOIL research projects (with weight in one or more of the knowledge framework compartments): scientists interact with each other and project interact with outer (blue ring) with society, policy and end-users.

Data management

In each project, data collection and storage should be standardized and harmonized as described in their individual data management strategies and the EJP SOIL data management plan (D1.6). The use of long-term experiments and soil research infrastructures of the partner institutes and countries is promoted.

Alignment with societal challenges

To assure alignment of research activities with knowledge users and target audiences, the EJP SOIL has set up national hubs comprised of stakeholders from a range of sectors (e.g., policy-makers, farmers, agro-industry, and civil society), and an advisory board consisting of scientists and influential stakeholders. Projects are encouraged to take a participatory approach with stakeholders (see chapter 3.3 of this document). This interaction is guided by a strategy for communication, dissemination and uptake as guided by the European Commission for stakeholder involvement.[19] Through a valorisation approach, projects may be linked to companies or other end-users like farmers and policymakers by making research directly relevant to society.

Interaction with stakeholders related to the knowledge framework and the Expected impacts

The EJP SOIL has five target groups: i) scientists, ii) policymakers, iii) farmers landowners and advisors, (iv) industry and agrobusiness and (v) members of the general public and civil society. Each target group is involved in different parts of the knowledge framework (Fig. 1).

1. Scientists: Scientists are mostly involved in the section of the knowledge framework focussed on knowledge development by being involved in research projects. However, scientist also are active in sharing and transferring knowledge to the new generation of scientists and also by disseminating their knowledge to other stakeholders.
2. Policy makers: Policy makers need the input from scientists to be able to design policies for society. For this, knowledge harmonization and ways to store and monitor soil information is highly needed. In turn, the knowledge on how to apply is key to this group of stakeholders.
3. Farmers, landowners, advisors: This group of stakeholders are mostly connected to knowledge application, as they are the ones that use and apply the knowledge generated in the whole framework. However, they also play a key role in identifying knowledge gaps and provide inspiration support for new research in the knowledge development compartment.
4. Industry and agrobusiness: This group of stakeholders is connected to knowledge application, as they may use and apply the knowledge generated in the whole framework. However, they will also identifyknowledge gaps and provide inspiration and support for new research in the knowledge development compartment.
5. Members of the general public and civil society: This stakeholder group mainly is involved in the knowledge sharing compartment of the framework, to be informed by the other stakeholders on the knowledge that is developed and applied. However, as practitioners, they can also play a role in identifying knowledge gaps and provide inspiration and support for new research in the knowledge development compartment.

To create the optimal environment for the EJP SOIL outputs to be used by stakeholders and reach the envisioned expected impacts, an inventory of the role of all stakeholders is needed. In addition, specific tools need to be developed to connect to each stakeholder group. In chapter 4.6 of this document different options for knowledge sharing and transfer for specific stakeholder groups (science-science, science-policy and science-society) have been described.

The stakeholder's relation to the Expected Impacts:

1. Scientists: this stakeholder group is key in the EJP SOIL programme as executers of the research in the programme. This stakeholder group is responsible for the (co-)design of

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[19] https://www.fch.europa.eu/sites/default/files/8.%20InfoDay%202020%20-%20Communication%20Dissemination%20Exploitation%20-%20Mirela%20ATANASIU%20%28ID%207922328%29.pdf

the research and other activities as described in chapter 4 with their respective outputs that cover research domains of the EJP SOIL.

2. Policy makers: This stakeholder group will utilize the provided outputs to design better informed policies, and as such assist in bringing the output towards the expected impacts. In addition, they also co-design the research by identifying knowledge gaps to the scientists.
3. Practitioners (‘Farmers, landowners, advisors’, and ‘Industry and agrobusiness’): These stakeholder groups identify their research needs and use the outputs from the targeted research projects. The developed knowledge and tools enable the practitioners to realize the expected impacts of the EJP SOIL.
4. Members of the general public and civil society: This stakeholder group may also bring forward new research needs, but will mainly benefit from the EJP SOIL research results by having a higher awareness of the role soil functions play in the sustainable use of our planet and finding suitable solutions for the pressing societal challenges.

Interaction with stakeholder within research projects of the EJP SOIL

Each project aims to have strong links with stakeholders in their research field and should be in contact and align with existing initiatives and NGOs. Stakeholders could, for example, be involved in a citizen science project doing research in a Living Lab environment or on a Lighthouse Farm. Stakeholders in the agri-food and financial sector are connected through the EJP SOIL projects, annual science days, and as essential stakeholders in the dissemination and outreach strategy to foster adoption of sustainable climate-smart soil management strategies.

Stakeholder interaction will be designed and planned for, based on identified outcomes (see Figure 5) and according to the activities described in chapter 4.6 of this document. In the coming years of the EJP SOIL the knowledge sharing and transfer plans will be adapted to the required needs that will emerge from the current EJP SOIL activities.

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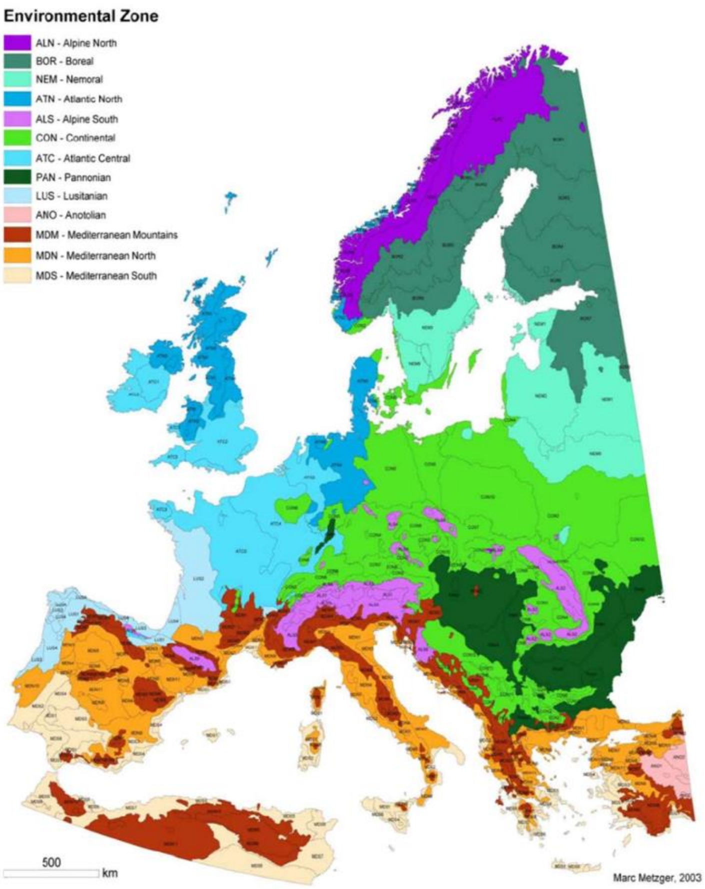
ANNEX 1: Maps for Regional diversity



Environmental zones of Europe according to Metzger *et al.* (2005): Alpine North; Boral; Nemorial; Atlantic North, Atlantic South; Alpine South; Continental; Atlantic Central; Pannonian; Lisitanian; Anotolian; Mediterranean Mountains; Mediterranean North; Mediterranean South.

Main European regions within EJP SOIL programme (adapted from StAGN 2020).

ANNEX 2: List of topics with a short description

In this Annex there are five types of call topic descriptions:

1. The topics that have been selected and put forwards in the first internal call
2. The topics that have been selected and are put forwards in the second internal call
3. The from which the 3rd internal call and external calls (1 and 2) will be selected

EJP SOIL Expected Impacts	Domains	2.1. Topics in 1st internal call (with projects financed)	2.2. Topics proposed in 2nd internal call	2.3. Topics from which the 3rd internal call and external calls (1 and 2) will be selected
EI 1/2	Climate change mitigation	CM2 - Quantification of the potential of agricultural soils to sequester more carbon at the regional and national scale in the different partner countries	CM1- Plant below-ground inputs to enhance soil carbon sequestration in agricultural soils	CM3 - Preserving and managing SOC in peatland and organic soils CM4/6- Understanding SOC sequestration (deep soil C, saturation, stoichiometry) CM7- Components of a European SOC MRV platform
		CM8 - Evaluating soil management options for specific objectives: Trade-offs between soil organic carbon sequestration, greenhouse gas emissions and/or N and P losses	CM5 - Effects of the soil biome on the persistence of SOC storage and its drivers	
EI 1	Climate change adaptation	CA1 - Evaluating soil management options for the specific objective of climate change adaptation - Synthesis	CA4/SP3 Contribution of soils to climate change mitigation and adaptation, sustainable agricultural production and environment in agro-ecological systems	CA3 Consequences of climate change and potential adaptation options on C, N and P cycling and potential adaptation options for managing them CA2 - Identifying viable farm-level incremental adaptation options, related to soil management, to respond to water impacts of climate change on agricultural soils: droughts, heavy rains and waterlogging
			SP1- Alleviating soil compaction in a climate change context	

EJP SOIL Expected Impacts	Domains	2.1. Topics in 1st internal call (with projects financed)	2.2. Topics proposed in 2nd internal call	2.3. Topics from which the 3rd internal call and external calls (1 and 2) will be selected
	Sustainable production	FS2/MT4 - Innovative soil management practices in Europe and their suitability for European farming systems - Stocktake	SP2- The use, processing and application of external sources of organic matter to mitigate climate change and improve soil health	SP4 Innovative technologies for diversified cropping and site-specific sustainable soil management
	Sustainable environment	SR5 - Landscape analyses: Erosion processes	SE2/INDICATORS 1: Modelling soil functions and soil threats for mapping soil functions and ecosystem services	SE5 Mitigate, adapt to salinization and restore soils: understanding the processes and improving cropping systems (with specific attention for irrigation) under current and future climate SE1 Site-specific landscape-scale analysis to design Nature-Based Solutions SE2 Good knowledge of the present status of agricultural soils to target region-specific soil threats
		ES1/ES2 - Methodologies and tools to assess the contribution of soils to ecosystem services / for assessing soil quality - Stocktake	INDICATORS 2/SE4 European soil biodiversity forecast towards resilient agroecosystems in response to climate change	SE6 Soil futures: scenario modelling for assessing the potential of climate-smart sustainable soil management to provide multiple ecosystem services SE3 Soil restoration: options and indicators for land degradation neutrality
EI4	Soil information	MT1 - Good knowledge of the present status of agricultural soils: Innovative techniques for soil mapping and assessing spatial and temporal variation of soil properties	DATA 1Innovative techniques to monitor SOC stocks and soil degradation/restoration changes in the EU, using spectral systems/NIRS/MIRS, and other proximal sensing tools	DATA 2 Feasibility of the mapping of soil management practices through remote sensing
				DATA 3 Estimation of soil physical degradation through remote and/or proximal sensing

EJP SOIL Expected Impacts	Domains	2.1. Topics in 1st internal call (with projects financed)	2.2. Topics proposed in 2nd internal call	2.3. Topics from which the 3rd internal call and external calls (1 and 2) will be selected
				DATA 4 Comparative analysis and harmonization of soil data analysed with different (ISO) standards
EI5	Adoption of sustainable soil management			NET1 Citizen science (including farmers) protocols to support science-based soil knowledge and site-specific policy applications
				AD1 - Regional Living Labs and lighthouses for healthy soils and sustainable farms
				AD2 Tools for evaluating and communicating soil quality for healthy soils and sustainable farms
				AD3 Soil-specific guidelines and decision support tools with focus on water storage, soil organic matter and nutrient use efficiency
	Science-policy interface		POL2/ES7 Enabling conditions for climate-smart and sustainable soil policy: fair and functional incentive systems for ecosystem services related to climate change mitigation and sustainable production	POL3 Support for soil and agro-ecological transitions across territories and agri-food chains for a circular bioeconomy POL1 Increasing soil protection and soil health within public policy
	Science-policy interface			POL4 New social and economic methods & scenarios for policy development POL5 Tools and models for supporting integrated soil policy

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 862695

Annex 2.1: Topics selected and put forward in the first internal call (full description)

CM2 - Quantification of the potential of agricultural soils to sequester more carbon and reduce GHGs emissions at the regional and national scale in the partner countries.

Rationale: To design adequate policies that promote climate change mitigation options in agriculture, countries need to know the potential of C sequestration in their conditions, at the national or regional scale, and in particular for agricultural soils. This potential depends on the pedoclimatic conditions, on the current soil organic carbon stocks and on the SOC storing practices that can be implemented.

Scope: The project will aim to evaluate the technical potential to store additional carbon in agricultural soils by implementing appropriate agricultural practices in cropland and grassland. Depending on the information available in countries on current SOC stocks, agricultural practices and soil properties, appropriate methodologies should be used. Either Tier 2 or Tier 3 approaches should be used, including modelling approaches, to estimate SOC stocks and their evolutions over a given time period, e.g. 20 or 30 years. Areas where soil carbon stocks are already important in EU should also be identified in order to define protection measures to prevent C losses. The estimate could be performed for a constant agricultural surface area or accounting for possible land use changes. Also, recent land use changes (e.g. cultivation of grasslands) are known to affect SOC stocks evolution and hence the baseline. In addition to a technical estimate, the cost of implementing the different management options should be estimated, in order to evaluate the cost of the quantified SOC additional storage potential in agricultural soils.

Output/Expected Impact: Improved spatially explicit quantification of the potential of agricultural soils to sequester more carbon and reduce GHGs emissions, under different cropping and soil management systems and under land use change, in different pedo-climatic conditions, at the regional and national scale, associated with an estimate of the incurred costs. Identification of EU agro-pedoclimatic regions regarding the SOC sequestration potential.

Project type: A single project is expected to be funded (large, 3 to 4 years, 350 PM), gathering partners from at least 20 participating member states (Annex 1). A synergistic effort of the different partners is called for. Core activities of this consortium would concern the methodology that can be used, defining a set of reference methodologies to be used. Each involved partner would then perform the evaluation for its own country, using the selected methodology.

Relation to EJP SOIL objectives and tasks: This project should consider outputs of EJP SOIL stocktake T2.4.3[20] published in the end of 2020 assessing carbon accounting systems and methods currently used in EJP SOIL countries to estimate SOC storage and storage potentials.

CM8 - Evaluating soil management options for specific objectives: Trade-offs between soil organic carbon sequestration, greenhouse gas emissions and/or N and P losses.

Rationale: Storing more C in soils may lead to adverse effects on the climate and on the environment, by increasing other GHG emissions (N_2O, CH_4) and by affecting water quality (nitrate leaching, eutrophication via P losses). Related to the type of farming systems (cropping and livestock systems), soil management strategies for C sequestration focus on increased input of organic matter (e.g. crop residues, cover crops, perennial crops, agroforestry, green manure, biochar, organic amendments), changes in the nature of organic inputs to soil (e.g. legume crops, organic amendments of different origins and quality such as compost, manures, etc) or decreased turnover of soil organic matter via either increased stabilization of SOC in mineral soils (manipulation of soil microbiome and soil fauna to increase formation of stabilized SOC, quality and CNP stoichiometry of organic matter inputs, spatio-temporal distribution of inputs) or by reducing the conditions prone to SOC turnover (e.g. increased level of groundwater table in previously cultivated and drained peatlands and organic soils). Many of these strategies have significant implications: e.g. rewetting of peatlands may greatly enhance methane emissions, adding livestock manures may enhance nitrous oxide emissions, nitrate leaching and phosphorus losses.

Scope: The objective is to analyse the potential trade-offs for major pedo-climatic zones and farming systems in Europe. The project will gather knowledge from past and current EU activities on quantifying the trade-offs and synergies, initiate and perform targeted measurements and/or modelling activities to fill in significant knowledge gaps, and synthesize knowledge into proposed robust indicators to predict trade-offs and synergies, as well as to propose measures to mitigate trade-offs. Indicator robustness should be assessed in term of applicability to a large diversity of soil management practices, soil types and pedoclimatic regions considering the different environmental and agro-climatic zones in Europe. Robustness could also rely on their possible validation through the comparison of predictions with available measured or estimated data on C storage and GHG emission.

Output/Expected Impact: Robust indicators to predict trade-offs and synergies, as well as measures to mitigate trade-offs.

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[20] The goal of T2.4.3 is stocktaking and synthesis on available knowledge of achievable carbon sequestration in mineral soils, including pasture/grassland across Europe, under different farming systems, soil types and pedo-climatic conditions as well as on GHG mitigation measures for managed organic soils. Here we specifically refer to the achievable carbon sequestration under specific land management, and not to carbon storage. C-sequestration as defined by Olson *et al.* 2014), *"the process of transferring CO_2 from the atmosphere into the soil of a land unit, through plants, plant residues and other organic solids which are stored or retained in the unit as part of the soil organic matter humus)."*

Project type: One to two medium size projects (150 PM), considering the specificities of organic versus mineral soils or contrasted climate conditions in Europe.

CA1 – Evaluating soil management options for the specific objective of climate change adaptation

Rationale: Although the role of sustainably managed soils and of organic matter rich soils is often put forward as a way to help agroecosystems to adapt to climate change, not much quantitative and context-specific information is available and synthesised.

Scope: In Europe, climate change affects soils through changes in the water regime (droughts, intense rains causing erosion), increases in temperature and increased pCO_2. The objective is to synthesize the available knowledge linking soil management, plant rooting patterns, soil structure and soil organic matter to crop water supply through effects on soil water (water harvesting, infiltration, retention, evaporation) and available knowledge linking soil management, soil biology and plant nutrients uptakes under elevated pCO2 and temperature. The benefits of soil carbon for adaptation to climate change will be reviewed as well as the effects of soil organic matter on soil structure and water-related properties that bring better resistance and resilience to modified climate. A large diversity of crops (annual and perennial crops, grasslands) and cropping systems (integrated crop-livestock farming systems, organic farming, conservation agriculture) should be considered. Contrasting soil management practices e.g. conventional vs reduced or no-tillage, cover crops, mulching, intercropping, agroforestry, etc.. would provide useful information on their potential for climate change adaptation through modifying soil structure, soil biology and soil water budgets. Important questions concern the dynamics (speed, duration, amplitude) of the observed changes in soil properties. Another key question will concern the response of different plant species to these changes and the consequences on the root distribution in the soil profiles. A special emphasis should be given to identify available knowledge about the interactions between the soil organic C inputs (aboveground and belowground), the activity of soil biota (microorganisms, micro, meso and macrofauna) and roots, the soil structure and related soil water retention properties in different soil types. This analysis will have to consider explicitly all European agro-climatic regions.

Output/Expected Impact: Quantitative, context specific information on how soil management options help agroecosystems to adapt to climate change and identified research needs.

Project type: A synthesis (20PM).

FS2/MT4 - Innovative soil management practices in Europe and their suitability for European farming systems

Rationale: Innovative farming practices are being developed, often by farmers themselves (e.g. highly diverse cover crops, mixed annual perennial crops, crops with deep rooting systems, intercropping, organic farming, agroforestry, integrated crop-livestock production, farm scale biogas production), and a high variability of the soil management practices developed and implemented is expected across Europe. An evaluation of the ability of such new management practices to succeed in achieving multiple goals is necessary. This should help to identify management practices or interactions between management practices, pedoclimatic context and/or agro-climatic zones that need knowledge development via EJP SOIL future internal calls for research projects.

Scope: This stocktake will first identify innovative[21] soil management practices and technologies, cropping and livestock agricultural systems in Europe developed by farmers, industry and research. Second, the study will evaluate the applicability and suitability of these and more well-known soil management practices and technologies for climate smart sustainable soil management for different pedo-climatic zones and farming systems in Europe. The practices and technologies described needs to address the EJP SOIL Domain "good agricultural soil management for: climate change mitigation and adaptation, sustainable production, ecosystem services and less soil degradation" and – whenever possible - have the potential to achieve multiple goals (e.g. pest and disease control). The practices/technologies may include cropping system technologies such as cover cropping, intercropping, green manuring, diverse rotations, systems with deep rooted crops, agroforestry systems, residue handling/mulching), tillage and traffic technologies (no-tillage, conservation agriculture, light machinery, low pressure tires/inflation pressure regulation), fertilization/manuring, amendment and biochar technologies, irrigation technologies. Novel technologies for improved spatio-temporal management of soils in terms of digital farming and precision agriculture would also be relevant to address. Further, the activity should deal with barriers to the implementation of such technologies, including economic incentives, regulations and lock-in situations, knowledge systems, and cultural barriers. This analysis will have to consider explicitly all European agro-climatic regions.

Output/Expected Impact: Identified innovative soil management practices developed by farmers, industry and research that are of interest for countries participating in the EJP SOIL. Identified assessed effects on EJP SOIL Domains (i.e. climate change mitigation, climate change adaptation, sustainable agricultural production, ecosystem services, soil rehabilitation). Trends of adoption and suitability for European farming systems given specific climatic constraints, barriers or enablers, and knowledge gaps.

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[21] "Innovation activities are all of the scientific, technological, organizational, financial and commercial steps, including investments in new knowledge, which actually, or are intended to, lead to the implementation of technologically new or improved products and processes." Frascati Manual 2002, OECD)

Project type: Combined stocktake (40 PM) collecting information from multiple countries.

ES1/ES2 - Methodologies and tools to assess the contribution of soils to ecosystem services / for assessing soil quality

Rationale:

Soil is the upper layer of the earth's crust, which fulfils multiple soil functions that are essential for human life. The soil`s natural functions are multi-fold as they i) ensure life through sustaining primary productivity and a large part of the overall biodiversity, ii) play a key role in the carbon, nutrient and water cycles and iii) control multiple natural processes (e.g. buffering, filtering). Evidently soil is useful to man as i) a source of raw materials, ii) land for settlement, economic and public uses, and iii) agricultural and silvicultural land use. However, the soil's capacity to sustain functions can be altered by a number of degradation processes, thus decreasing their capacities to provide ecosystem services.

Scope: Evaluate the ability of agricultural soils to sustain functions and ecosystem services and thereby evaluate their quality requires to have: i) an explicit framework and chain from soil properties to soil functions and to soil ecosystem services, ii) indicators of soil state and functions, and iii) a set of reference values for these indicators, in the different pedo-climatic conditions for the main agricultural productions.

Therefore, the study will review the main approaches developed and published in the literature, in EU wide programmes (MAES) and in EU projects (e.g. LandMark) and whether they use indicators of soil properties (soil state), soil functions or of soil ecosystem services. Integrated approaches developed to assess trade-offs and synergies between soil ecosystem services will be targeted.

The study will stocktake what is used in EJP SOIL partner countries and whether assessments on the links between soil properties, functions and ecosystem services have been translated into policy implementation/land management options in the participating member states. Transferability and actual transfer of methods to farmers and citizens through participatory science approaches should also be examined.

The study will also stocktake the sustainable values of SOC, soil fertility, soil biodiversity and degradation risk and associated target values of indicators, available in the literature, or already used at regional or national scale. The definition and use of references for these indicators will be analyzed. This analysis will have to consider explicitly all European agro-climatic regions.

Output/Expected Impact: Inventory of **i)** evaluation frameworks for ecosystem services / soil quality in use in Europe and of the associated knowledge and development needs, and **ii)** desirable values of SOC, soil quality, soil biodiversity and degradation risk and associated target values of indicators and identification of the knowledge needs for given pedo-climatic and agricultural system contexts.

Project type: A combined stocktake (40 PM).

Relation to EJP SOIL objectives and tasks: This stocktake should consider outputs of a WP2 stocktake T2.4.2[22].

SR5 - Landscape analyses: Erosion processes

Rationale: The 7th Environmental Action Plan of the European Union[23] stated that by 2020: "land is managed sustainably in the Union, soil is adequately protected". Achieving these goals require efforts in reducing soil erosion and increasing soil organic matter content. Land use aspects are to be integrated and coordinated with decision-making, all relevant government levels need to be involved. Soil and land need to be acknowledged as a resource, and targets for land planning and sustainable land and soil use and management should be defined addressing soil quality issues within a binding legal framework. Erosion processes (detachment, transport, and deposition) result in the loss of soil and SOM due to water and wind erosion in agricultural fields. Where does it occur? How can it be assessed? What is the impact and how can it be prevented?

Scope: Viewing erosion at the landscape scale is essential to answering these questions and can aid the development of climate-smart sustainable management strategies and interventions that will increase carbon storage within the landscape without incurring degradation elsewhere. The project should consider the 'connectivity' principles to identify key linkages between soil loss and associated impacts on carbon cycling, biodiversity and water resources. Introduction of agroecology principles in order to conceive landscapes more resilient to climate change and soil degradation could be considered. Field observatories with long term records on soil erosion and related soil properties (soil aggregation, wettability) in relation with the implementation of soil management practices and agroecological infrastructures as well as modelling approaches at the landscape scale to test different land use scenario will be particularly useful. Projects should focus on multiple European environmental zones and soil types.

Output/Expected Impact: An analysis of erosion processes and associated impacts at the landscape scale. Proposals for landscape designs and management options aiming at erosion control.

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[22] The goal of stocktaking 2.4.2 is to gather information on soil quality indicators and associated decision-making tools. The term soil quality encompasses a broad spectrum of features and considers functional ability together with the response properties of the soil. Soil quality, therefore, provides complex information on the sum of different soil characteristics, with regards to the level of ecosystem services a soil can provide. The partners collect information for this stocktaking and deliver it by filling a questionnaire in excel relating to soil quality indicators in terms of ecosystem services providing. It is a simply structured excel database for the stocktaking of all indicators commonly used in countries and used for decision support tools.

[23] https://ec.europa.eu/environment/action-programme/

Project type: Medium size research project (150 PM).

Relation to EJP SOIL objectives and tasks: A recent COST Action (ES1306: Connecting European Connectivity Research; 2014-2018) focused on the topic of water and sediment connectivity from plot to catchment scale. Attention was given to theory development, measuring and modelling approaches, indices and how the concept of connectivity can be useful for society. The COST Action involved all 37 countries connected to COST.

MT1 - Good knowledge of the present status of agricultural soils: Innovative techniques for high-detail soil mapping and assessing spatial and temporal variation of soil properties

Rationale: Soil is a complex mixture of organic and inorganic constituents with different physical, chemical and biological properties, that shows large variability from site to site or even within the same field. Spaceborne and airborne remote (hereafter as “remote”) sensing has several benefits such as obtaining soil surface and topsoil information from large areas, providing information for inaccessible areas, providing additional data (e.g. status of vegetation), consistent temporal resolution for creation of time series, short revisit time and providing free data. Remote surveys have the advantage to map larger areas however in low resolution and artefacts due to soil roughness, moisture and vegetation litter affecting accuracy of SOC estimation. Although several attempts to improve accuracy of remotely mapped soil properties were undertaken, none of these approaches is capable to assess soil properties in the desired resolution and accuracy. Combining these technologies into EU observation network could also interestingly rely on participatory science approaches.

Scope: This project will focus on developing and testing these innovative approaches (novel technologies and sensors but also low cost and low-tech approaches used in participatory science) for measuring soil characteristics (e.g. soil moisture, soil salinity, SOC, soil biodiversity) and soil evaluation, in the different environmental zones and soil types in Europe.

Output/Expected Impact: Novel technologies and approaches available for measuring soil characteristics and evaluating soils

Project type: One to two medium size research projects (per project 150PM). This topic will also be proposed in the second EJP SOIL internal call.

Annex 2.2: Topics selected and are put forward in the second internal call (full description)

CM1- Plant below-ground inputs to enhance soil carbon sequestration in agricultural soils

Rationale/Specific challenge: Soil organic carbon sequestration qualifies as a significant GHG removal technology, at a low cost compared to other negative emission technologies (IPCC 2019). The Green Deal increased Europe ambitions regarding climate change mitigation with an objective of zero net GHG emissions by 2050 (European Commission, 2019)[1]. There will be the need to use the full potential of European Soils for mitigation and adaptation strategies, in particular by increasing the soil organic carbon pool in agricultural soils by implementing sustainable soil management practices (Montanarella and Panagos, 2021)[2]. Agricultural soils have indeed a key role to play as they have lost huge amounts of soil organic C since the advent of agriculture (Sanderman *et al.* 2017)[3] and have thereby a large potential to store additional carbon and sequester CO_2 from the atmosphere, through appropriate soil and crop management options (e.g., Smith *et al.* 2008).[4] There is an increasing agreement that crop root systems are major determinants of increasing topsoil and subsoil SOC stocks. Increasing below-ground C inputs to soil may be achieved by a variety of management options, from the selection of varieties of annual crops with deep rooting and large allocation to their below ground parts, to the implementation of cover crops, of multispecies cropping systems, of high diversity grasslands, or silvo-arable or silvo-grassland agroforestry systems. The present knowledge does not allow, however, to predict root-derived SOC storage nor its persistence in agricultural soils as related to root traits or functions, or soil and climate characteristics in the different soil cover and management systems.

Scope: The project will aim to assess the contribution of belowground parts of plants to soil C and its persistence for a diversity of agricultural systems and management practices. Proposing relevant descriptors/root traits (e.g., root biomass, root architecture, rhizodeposition) is necessary to predict the effect of root systems on SOC stocks. Both experimental and modelling efforts are required to make progress in the understanding of the effects of the diversity of systems (e.g., intercrops, cover crops, diverse grassland plants, agroforestry) on C allocation to below ground parts of plants (shallow or deep roots, mycorrhizas and rhizomes) and their residues and rhizodeposits, as well as their control by soil type and climate. Combining synthesis and meta-analysis of field experiments with modeling approaches will be particularly useful to assess the C sequestration potential of the different rooting systems. The project should contribute to the root/shoot database for C-input data to the soil developed by the EJP SOIL CarboSeq project; and, to identify the co-benefits of deep rooting systems. The latter should consider adaptation to drought events and climate change, reduction of N leaching, promotion of habitats for soil biota, protection from erosion and evaluating trade-offs with yield maintenance and potential additional GHG emissions.

Expected outcomes:

- Sound scientific evaluation of the C sequestration potential, co-benefits and trade-offs of selected management options and agricultural systems (e.g., annual crops or perennial systems) resulting in increased and deeper OC belowground inputs.
- Improved knowledge on root traits for annual and perennial plants usable by plant breeders.

Expected Impacts:

- EJP SOIL EI1: Fostering understanding of soil management and its influence on climate change mitigation and adaptation, sustainable agricultural production and environment.
- EJP SOIL EI2: Understanding how soil carbon sequestration can contribute to climate change mitigation at regional level including accounting for carbon.

Project Type: Medium size research project (up to 2M€).

CM5 - Effects of the soil biome on the persistence SOC storage and its drivers

Rationale/Specific challenge: Agricultural soils are currently facing a decrease in soil biodiversity (abundance and diversity of soil biota) as a consequence of intensification, simplification of crop rotations or monocropping, mechanization and excess use of pesticides and fertilizers (FAO, ITPS, GSBI, SCBD and EC, 2020). Preserving and restoring soil biodiversity is now recognized as a major challenge at the EU level (Veerman **et al.** 2020)[5]. The EU Biodiversity Strategy expresses the ambition of the EU to reverse biodiversity loss (European Commission, 2020)[6] and its targets with that of the Farm do Fork Strategy (European Commission, 2020)[7] of reducing the use of pesticides by 50% in 2030, achieving 25% of total farmland under organic farming by 2030 and at least 10% agricultural land under landscape features with high biodiversity, should have a positive effect on soil biodiversity. Farming practices and agricultural systems have a major effect on the soil biome (fauna and microbial communities) and its functioning (e.g. carbon use efficiency). Yet, the extent to which soil biome controls SOC sequestration and whether this can be managed is not sufficiently known and such knowledge is needed for recommendations of management options that preserve or increase soil organic carbon stocks. For instance, in organic agriculture as yields are generally lower, organic inputs are consequently smaller, but SOC stocks can be maintained or even increased which is ascribed to changes in the carbon use efficiency of soil microorganisms. The importance of stoichiometry, especially carbon/nitrogen/phosphorus ratios, in controlling carbon use efficiency by soil organisms and its consequences on the balance between SOC storage and GHG emissions also warrants further research.

Scope: The project will aim to study the relationships between soil carbon cycling and the diversity of the soil microbiome and fauna. An important question is the effect of soil management practices, especially through the stoichiometry of organic matter inputs (crop residues, organic amendments, below ground inputs from plants) on the carbon use efficiency of soil microorganisms and, ultimately, on SOC sequestration. The effects of soil biome on SOC sequestration should be investigated in real case-studies (on-farm and/or experimental field sites) representing a diversity of soil management and pedo-climatic conditions. A special focus should be placed on the identification of the drivers related to soil status and management, which may favour or hamper the adequate functioning of soil microbial communities regulating SOC sequestration. The measures and agricultural systems included in the Green Deal targets could be considered. Improving existing biogeochemical SOM models by incorporating new knowledge on the effects of soil biome on carbon and nitrogen cycles should also be investigated in order to evaluate the trade-offs between SOC storage and GHG emissions.

Expected outcomes:

- Identifying drivers related to soil management effects on soil biome which may enhance/prevent SOC sequestration and other co-benefits in different EU pedo-environmental zones.
- Qualifying farming systems promoting soil biodiversity in terms of their potential for mitigating climate change (increased SOC sequestration, decreased GHG emissions).

Expected Impacts:

EJP SOIL EI2: Understanding how soil carbon sequestration can contribute to climate change mitigation at regional level including accounting for carbon.

CA4/SP3 Contribution of soils to climate change mitigation and adaptation, sustainable agricultural production and environment in agro-ecological systems

Rationale/Specific challenge: Agro-ecological systems are characterized by higher biodiversity at all levels (intra- and interspecies, cropping and farming systems, landscapes and non-agricultural elements) than traditional high intense agricultural systems. Such agro-ecological systems are potentially better adapted to local environmental conditions and to social and economic requirements. Transition of current agriculture to agro-ecological systems leads to more sustainable and climate responsive agricultural production. Such a transition is a relevant contribution to the implementation and success of the EU Green Deal and EU policies on Biodiversity, on circular economy and on climate change. This approach towards agro-ecological systems fits the recommendations by the Mission Board on Soil Health and Food and the Farm to Fork Strategy and will contribute to reach the target “25% of agricultural land under organic farming”.

This agro-ecological transition can be considered as a high potential opportunity to respond in particular to changes and challenges posed by climate change across the European continent. Examples and experiences include better soil exploration by deep rooting in mixed crops or deep rooting crops to enhance water and nutrient availability. Also, facilitation of symbiosis of roots with microbes may enhance nutrient uptake. More soil carbon will stimulate soil biodiversity and enhance resilience to climate change and climate variability and ability of soils to sustain more frequent extreme events (prolonged drought, extreme wet conditions, extended warm periods, and higher risk for diseases to occur). However, the impact of the transition to agro-ecology on the resilience of agroecosystem to climate change in many European regions is poorly understood and documented, especially for its soil component. Understanding and quantifying this impact is particularly relevant when the climate is changing and forces local and regional agricultural systems to adapt.

To date, most long-term experimental studies and meta-analyses on the effects of management on agricultural soils have focussed on the impact of a single practice or a specific technology. As a consequence they have not considered scope and options of the full context of an agro-ecological farming system, nor considered the broad range and diversity of agricultural systems that exist in Europe. These alternative and new systems and practices need to meet multiple goals on soil health, agricultural production, climate change adaptation and mitigation and support and sustain ecosystem services. These systems also need to be recognized by local farmers to fit their specific conditions and socio-economic needs and perceptions.

Several recent H2020/FP7 projects among others have investigated elements concerning soil degradation processes and remediation practices, the assessment of soil's contribution to the provision of ecosystem services and relations to climate change mitigation. This project will utilize and build upon the knowledge and data provided in these recent and completed FP7/H2020 projects.

Scope: The agro-ecological systems and the underlying climate-smart sustainable soil management practices considered in this project will be selected on their *a priori* positive effect on climate change adaptation and mitigation (e.g., agroforestry, conservation agriculture, organic farming, integrated crop-livestock-forestry systems). This will be combined with their actual adoption or potential for adoption by farmers in climate regions and agro-ecological zones across the EU and relate to the projected climate change. This will require the sourcing and use of results of completed projects and existing data in EJP SOIL.

The research will evaluate soil functions and ecosystem services provided by soils in relation to climate change adaptation and mitigation. This will include the provisioning service for food, the ability of the soils to contribute to climate change mitigation (conserve or increase SOC stocks, decrease N2O emissions), and the ability of soils to contribute to climate change adaptation (e.g. soil water infiltration & storage and yield stability). The research will use available tools (existing models and indicators). The project will identify and use, and adapt if needed, a series of long term and highly instrumented case studies in different pedo-climatic conditions. This will be based up on long term experiments (LTE's) of the EJP SOIL consortium allowing for retrospective analysis of soil conditions, crop yields and climate conditions and change. In complement, the project will also identify pioneer farmers in different EU countries as lighthouse farms to enhance the regional applicability and allow farmers to recognize their local conditions and systems. This research could also be performed by modelling the complex soil – plant interactions in agro-ecological systems, to evaluate them regarding their resistance and resilience under different climate scenarios (RCPs). These different research approaches can be combined.

Expected outcomes:

- Identify and report on the effect of climate variability across EU agro-ecological zones on soils and crop in various agro-ecological systems.
- Assess the impact and contribution of soils and soil management across the range of agro- ecological systems to climate change mitigation and adaptation and relate to future regional climate conditions.
- Develop and propose guidelines for soil management to fit the complex and diverse agro- ecological systems in different EU pedo-climatological and environmental zones.

Project outcomes should feed into the to be realised partnership on agro-ecology and living labs

Expected Impacts:

- EJP SOIL EI1. Fostering understanding of soil management and its influence on climate change mitigation and adaptation, sustainable agricultural production and environment.
- EJP SOIL EI5. Fostering the uptake of soil management practices which are conducive to climate change adaptation and mitigation.

Project Type: Large size research project (up to 5M€).

SP1 Alleviating soil compaction in a climate change context

Rationale/specific challenge: Soil compaction is considered a major European soil health challenge, and a threat for the soils' capacity to deal with climate change mitigation and adaptation. The historical changes of compaction levels were shown to coincide with a stagnation in crop yields in the 1990s for cereals in many European countries (Keller **et al.** 2019)[8]. Soil compaction restricts root growth and thereby the uptake of nutrients and water leading to yield losses and reduced carbon input to both top- and subsoil. Soil compaction also affects the timeliness of soil operations especially in a changing climate, which may also affect crop yields (Kolberg **et al.** 2020)[9]. Thus, alleviation of soil compaction is critical for sustained or increased soil carbon storage and accounting for soil compaction effects may be necessary in forecasting the evolution of SOC stocks in European soils. Climate change is also expected to strongly worsen the soil compaction problem. Impeded root growth due to soil compaction will aggravate effects of more frequent droughts with detrimental effects on yields and carbon input. Soil compaction-induced restricted water transport will also exacerbate problems with flooding in a future climate with more extreme rainfall events (Keller **et al.** 2019). There is a strong need for an analysis of the impact of climate change on the extent and the effects of soil compaction. The extent and severity of the soil compaction challenge is strongly related to soil management in terms of field traffic with heavy machinery and livestock trampling. The extent of the soil compaction and the impacts on climate change adaptation, soil carbon storage and soil health in general needs to be quantified at EU scale for different pedo-climatic conditions and cropping systems. Strategies to limit the risk of soil compaction in a climate change context need to be developed with focus on traffic intensity, weight of machinery and timing of operations. Novel advanced technologies in the field of digital farming and robotisation may be applied to significantly reduce the soil compaction problem, but this has been scarcely researched. There is also a need for better knowledge on the recovery of compacted soil and the development of biobased strategies to stimulate recovery.

Scope: The scope of project is to analyse how climate change affects the extent of soil compaction and how soil compaction affects the capacity of soils to adapt to climate change and mitigate it. For this the project will quantify the extent and severity of the soil compaction problem at EU scale for different pedo-climatic conditions and cropping systems considering both topsoil and subsoil compaction. The project will analyse and develop management strategies that reduce risk of compaction and stimulate the recovery of compacted soil. Management strategies will be developed and tested in collaboration with farmers. The project will gather knowledge from past and current EU and national activities and initiate targeted measurements and modelling activities to fill in significant knowledge gaps.

Expected outcomes:

- Analysis of the impact of soil compaction in a changing climate.
- Quantifying the extent and severity of the soil compaction problem for different pedo-climatic conditions and cropping systems under climate change.
- Improved knowledge of management strategies and technologies to reduce risk of soil compaction and the recovery of compacted soil in a climate change context.

Expected Impacts: EJP SOIL EI1 Fostering understanding of soil management and its influence on climate change mitigation and adaptation, sustainable agricultural production and environment.

Project Type: Medium size research project (up to 2M€).

SP2 - The use, processing and application of external sources of organic matter to mitigate climate change and improve soil health

Rationale/Specific challenge: Encouraging the recycling of organic wastes into renewable fertilizers or amendments and promotion of shorter value chains and circular (bio)-economy to improve soil health is a priority in the EU agenda (Farm to Fork Strategy, Green Deal, Mission Board for Soil health and food, Horizon Europe). The Green Deal increased Europe ambitions regarding climate change mitigation with an objective of zero net GHG emissions by 2050 (European Commission, 2019)[10]. There will be the need to use the full potential of European Soils for mitigation and adaptation strategies, in particular by increasing the soil organic carbon pool in agricultural soils by implementing sustainable soils management practices (Montanarella and Panagos, 2021)[11.] Adding external sources of organic matter to soils as fertilisers or amendments is a sustainable management option (FAO, 2018)[11]. Adding manures and composts has been considered in several previous EU projects as part of soil improving cropping systems and best management practices. An increasing diversity of new organic resources are becoming available for farmers (biochars, digestates, human wastes derived fertilizers) besides more traditional ones (composts, manures). Yet, these resources remain insufficiently studied in terms of SOC storing capacities, GHG balance, improvement of the capacity of soils to infiltrate and retain water, fertilizing values and nutrient losses and environmental safety due to the potential presence of contaminants. More generally, the characterisation of organic wastes is insufficiently developed to guide their use for selected objectives such as climate change mitigation. This lack of knowledge hinders the optimal integration of organic wastes in farming systems for climate change mitigation and sustainable production. Increasing organic waste valorization under a circular approach brings also new questions at the territory level, as related to the organizational links between arable crops and animal farming, urban and rural areas, agriculture and waste recycling sectors.

Scope: The aim is to gain knowledge on the use, processing and application of external sources of organic matter to mitigate climate change while maintaining sustainable production and improving soil health. The project will consider:

- What is the impact of resource quality of the range of potential external organic matter sources on SOC storage and stabilization.
- What is the impact of climatic conditions, soil characteristics and initial soil organic matter contents (pedo-climatic zones) on the expected life time of organic C additions across soils.
- What - if any - restrictions apply to the amount of exogenous organic matter that can be added safely (no loss of soil quality) and effectively in terms of climate change mitigation (*net* gain of SOM and *net* reduction of GHG emissions without trade-offs).
- What are preferred management options in terms of how and when to amend exogenous organic matter considering soil depth, ploughing, fertilization, irrigation, and accounting for approved standards for safe and effective use of organic amendments.

What processing options before returning organic matter to soils are available and effective to enhance formation of stable organic matter in soils as compared to direct return and how can technologies be evaluated. The project should determine what is the C budget and the impact on GHGs and nutrient release during processing and storage and after soil application. Potential trade-offs and thresholds between short-term nutrient release and long-term C sequestration should be analyzed.

The project should carry a synthesis of existing knowledge, integrate information from on-going experiments (including EJP SOIL long-term experiments) and perform targeted new studies on the short- and long-term effect of organic resources for different pedo-climatic conditions and cropping systems. The knowledge gained will be used to refine existing decision support tools for selecting suitable and cost-efficient strategies at the territorial level to make the best use of the local organic resources accounting for agro-pedoclimatic characteristics, crop and farming systems, organic resource availability, production and transport costs. The aim is to include in such decision support systems several criteria and soil functions (carbon sequestration and GHGs emission, nutrient cycling, soil structure, soil biodiversity) and to lead to recommendations of standards for safe and effective use of organic resources that allow for climate change mitigation (targeting farmers and also the waste recycling sector).

Expected outcomes:

- Improvement of knowledge of the capacity of traditional and new external organic resources to mitigate climate change, while maintaining sustainable production and soil health.
- Better capacity (knowledge and proposed tools) to make the best use of local organic resources, considering the advantages/ drawbacks of processing options before adding the organic resources to soil and considering organic resource availability at the territory scale.

Expected Impacts:

- EJP SOIL EI1: Fostering understanding of soil management and its influence on climate change mitigation and adaptation, sustainable agricultural production and environment.
- EJP SOIL EI2: Understanding how soil carbon sequestration can contribute to climate change mitigation at regional level including accounting for carbon.
- EJP SOIL EI6: Developing region-specific fertilization practices considering the local soil, water and pedo-climatic conditions.

Project Type: Medium size research project (up to 2M€).

DATA1 - Innovative techniques to monitor SOC stocks and soil degradation/restoration changes in the EU, using spectral systems/NIRS/MIRS, and other proximal sensing tools

Rationale/Specific challenge: SOC stocks and soil quality (degradation/restoration) evolve under the combined effects of land use, soil management and climate change. These dynamics may be quite fast (decades) and are insufficiently known and monitored as traditional monitoring methods are expensive and time consuming. Much faster and high throughput methodologies of soil characterization are needed to meet the needs of soil policies, such as assessing changes in soil condition, SOC and erosion rates under agricultural management in the CAP context, or assessing soil nutrient status in the context of the Farm to Fork strategy targets (European Commission, 2020)[16]. Soil spectroscopy (both near and mid infra-red, i.e. both NIRS and MIRS) has been developed in the last years and various proximal sensing techniques offer promising technologies to speed up and reduce the costs of the soil surveying activity. Spectral libraries already exist at different levels: national (or regional) spectral libraries in several of the EJP SOIL partner countries and the LUCAS spectral library that is the most comprehensive and freely available. Some initiatives for combining and harmonizing these spectral libraries also exist, such as the work made by the GLOSOLAN working group on spectroscopy. However, there is still a need for further harmonization of spectral measurements. Calibration in relation to the laboratory analysis as well as producing procedures to derive soil parameters from soil spectra are needed to fully validate these techniques and allow them to be deployed at a large scale in Europe. Proximal sensing is complementary to remote sensing approaches developed, e.g. for SOC monitoring, in the EJP SOIL STEROPES project and in the ESA WorldSoil projects.

Scope: The project will focus on the use of proximal sensing for soil monitoring in the field, and will aim to validate proximal sensing techniques for estimating soil properties (e.g. carbon content, soil texture, pH, nutrient contents etc.). The project should investigate the reliability and applicability of such spectroscopic techniques. A key point will concern calibration of the different estimated soil properties with actual measured data. Developing inter-comparisons is relevant for this topic, e.g. the same soil samples contemporarily analysed by reference European or European laboratory and scanned for its spectra. Using freely available spectral libraries such as LUCAS, national and other spectral libraries and cooperation with international spectroscopic harmonisation activities (like GLOSOLAN, IEEE) is encouraged. A critical analysis of innovative tools and methods in terms of accuracies and harmonization of soil spectral libraries is expected in order to evaluate their potential use for rapid and low-cost assessment of soil properties. The project should deliver a list of soil characteristics that can be determined by validated proximal sensing methods.

In a possible secondary step, this project could also determine the advantages and limitations of combining proximal and remote sensing. This combination would permit to enlarge the evaluations done at one site by proximal sensing, to larger areas, using the same sensors (for example VIS-NIR). For this step, cooperation should be sought with the EJP SOIL project STEROPES and WorldSoils and possibly other research initiatives.

Expected outcomes: Improving the development and availability of proximal sensing methods allowing to speed-up the monitoring of soil characteristics in the field that could possibly be used directly by farmers (citizen science) or for soil monitoring at the national and the European scale.

Expected Impacts:

- EJP SOIL EI1: Fostering understanding of soil management and its influence on climate change mitigation and adaptation, sustainable agricultural production and environment.
- EJP SOIL EI4: Supporting harmonised European soil information, including for international reporting.

Project Type: Medium size research project (up to 2M€).

SE2/INDICATORS 1 Modelling soil functions and soil threats for mapping soil functions and ecosystem services

Rationale/Specific challenge: Modern agriculture is in many cases contributing to continued soil degradation. The effects are severe depletion of soil organic matter (SOM) content, accelerated erosion, reduced soil water holding capacity, loss of soil biodiversity, salinization, soil pollution and increased GHG emissions (FAO and ITPS, 2015[12]; EEA, 2015; 2019[13]). These ongoing degradation processes impede agricultural soils to fully contribute to the provision of ecosystem services such as food and fibre production, climate change mitigation, disaster management (floods and droughts) and biodiversity-based control regulations (IPBES, 2019; 2019; IPCC, 2019; ECA, 2018[14]). In addition, there is an increasing need to be able to assess and predict the ability of soils to perform given functions for implementing climate-smart sustainable management options. Recently, several EU projects have concerned the reporting on soil degradation processes and the assessment of soil contribution to the provision of ecosystem services. Different concepts (e.g. soil quality, soil health) and indicators have been implemented across countries. Some indicators have been used in decision support tools to assess the multi-functionality of soils. However, indicators based on soil properties still need to be improved, tested on a variety of pedo-climatic conditions and shared with end-users (farmers). Also, common reference and/or threshold values have to be set, covering the diversity of soil types, climatic conditions and agricultural production systems at the European scale.

Scope: The EJP SOIL funded a first project to take stock on existing indicator systems for assessing soil quality and ecosystem services, including reference values for agricultural soils, as currently used by Member States associated in the EJP SOIL and beyond. However, the validity of these indicators and reference values remains to be tested to be able to produce detailed map of soil functions at the EU scale. Therefore, the main aim of the project is to use, test and improve the robustness and sensitivity of existing indicators and their interpretation values (e.g. reference and/or threshold values) to model and map soil functions and related ecosystem services, focusing especially on climate change adaptation and mitigation.

Interpretation/ reference values should be evaluated and, or, developed for different combinations of soil types and agricultural land uses (cropland, grassland, agroforestry). Such values should ideally be defined in collaboration with the JRC/ESDAC and DG ENV. The project should consider region-specific challenges since soil threats differ among EU regions. Modelling and mapping issues should particularly concern the temporal dynamics of soil degradation and soil functions as related to climate change and changing agricultural practices and land-use (cropland, grassland, agroforestry). The project will release a geodatabase on soil degradation and soil functions based on tested indicators at the EU scale. The relevance and incurred cost of using these indicators will be analysed from a policy perspective. Participatory approaches involving end-users and farmers are encouraged, in order to share knowledge on the multi-functionality of soils, to test and improve soil indicators and decision-support tools in real local conditions and to demonstrate the benefits of climate-smart sustainable soil management.

Expected outcomes:

- Improving decision-support systems for farmers adapted to different EU agricultural systems and soil conditions and helping to evaluate and design best management options.
- Improving availability of models and geodatabase allowing to assess the effect of ongoing/possible soil threats and/or of agricultural soil management options on the provision of soil functions and ecosystem services. Knowledge allowing for a better harmonization of systems and references for evaluating soil functions and ecosystem services across Europe.

Expected Impacts:

- EJP SOIL EI1: Fostering understanding of soil management and its influence on climate change mitigation and adaptation, sustainable agricultural production and environment.
- EJP SOIL EI4: Supporting harmonised European soil information, including for international reporting.
- EJP SOIL EI5: Fostering the uptake of soil management practices which are conducive to climate change adaptation and mitigation.

Project Type: Large size research project (up to 5M€).

INDICATORS 2/SE4 European soil biodiversity forecast towards resilient agroecosystems in response to climate change

Rationale/Specific challenge:

Soil biota are key in the functioning of soils and their contribution to ecosystem services. Yet, relatively little is known about the functional role of soil biodiversity and how belowground functional biodiversity can be stimulated to enhance soil functioning or provide resilience to climate change and adverse conditions such as drought or soil borne diseases. Little is also known as to what levels of biomass or activity of the soil biota would be desirable in the perspective of sustainable and climate- smart agriculture and the provision of multiple ecosystem services including climate change mitigation and soil borne disease controls.

The current status of soil biodiversity in Europe waits to be assessed (FAO-GSP-ITPS 2020[15]). Therefore, both scientific research and policy instruments are needed. In particular in the light of EU Biodiversity Strategy, advances are expected concerning the development of functional indicators and target values for healthy soils and the expected soil functions and ecosystem services, in relation to soil types, land uses and climate zones to cover all relevant (soil) conditions.

Scope:

The project is expected to use concepts, results and samples from previous projects and long term experiments available through EJP SOIL partners. The project will be complementary to ongoing national and H2020 projects and in doing so will cover all regions and climate conditions across EU27. The objective is to provide at the European scale, regionalized maps of soil biodiversity and biodiversity decline, for various biological groups (bacteria, fungi, micro, meso and macro invertebrates) and selected associated functions (e.g. organic matter decomposition, nutrients provision, water retention, susceptibility to soil borne diseases) in agricultural soils. This will require the identification and selection of relevant indicators describing soil biodiversity from previous and ongoing projects. The focus will be especially on selected taxonomical and functional indicators and their evolution as a result from both climate conditions and from implementation of specific soil management actions to respond to climate change. Reference values for the selected functional indicators will be identified and time series established from archived soil samples to relate biodiversity to climate conditions and climate changes anticipated.

Time series of chrono sequences on soil biodiversity records in relation to climate sensitivity would be particularly helpful to indicate sensitivity to climate and agricultural soil use, e.g. from LUCAS or other archived soil samples and using PCR / DNA technology or other identification methods. The project will collect existing biodiversity data by EJP SOIL partners and EU countries. It will also use the existing knowledge and metadata related to soil type (national and commercial soil analyses; EJP SOIL Meta database), agricultural land use (cropland, grassland, agroforestry) and soil management in order to develop models for mapping soil biodiversity and related functions. Options will be identified to manage soil biodiversity and enhance soil quality and the challenges to adequately respond to climate change.

Expected outcomes:

- Proposing functional indicators of soil biodiversity in relation to soil ecosystem services by connecting to existing and complementing the framework with the relevant parameters developed in e.g., SFS_21 projects and national programmes where appropriate;
- Sourcing data from previous projects and commercial soil analyses to produce maps of the current values and/or levels of these indicators at the EU scale to identify regional differences;
- Providing for climate responses and sensitivities of soil biodiversity indicators on the basis of archived soil analysis;
- Identifying thresholds and target values for biodiversity indicators and identification of policy instruments to address and enhance soil quality where appropriate with measures and actions.

Expected Impacts:

- EI1 Fostering understanding of soil management and its influence on climate change mitigation and adaptation, sustainable agricultural production and environment.
- EI4 Supporting harmonised European soil information, including for international reporting.

Project Type: Medium size research project (up to 2M€).

POL2/ES7 - Enabling conditions for climate smart and sustainable soil policy: fair and functional incentives for ecosystem services related to climate change mitigation and sustainable production

Rationale/Specific challenge: Soil is part of the natural environment in the same way as air and water, however, there is no direct policy at the EU level dedicated to soil protection or enhancing the capacity of soil to provide different functions (primary productivity, nutrient cycling, water purification and regulation, climate regulation with C sequestration and habitat for biodiversity and biological processes). Across the EU, and more globally, there is increasing awareness of climate change and biodiversity losses, their linkages and impacts amongst society. Growing concerns about soil health, carbon sequestration and climate change mitigation are compelling governments to develop policies to protect their citizens' health and livelihoods, their natural environment and resources. Healthy soils, in direct line with human health and ecosystem health, is and become a more and more important topic for policy makers. The Mission Board on Soil Health and Food had proposed an ambitious target that 75% of European Soils and Healthy by 2030 (Veerman **et al.** 2020)[14.].

To enable the creation and updating of soil related policies, a number of conditions are currently prohibiting the payment schemes for ecosystem services provided by soils, that would help to give soil a higher value in policy and public perception. Farmers, especially from low-income categories should be encouraged with such payments, in particular through carbon farming schemes. A challenge is to account for the large diversity of farms between and within EU countries. Research is needed to support policy stakeholders to visualize the different challenges for climate-smart and sustainable soil management across different spatial scales, farming systems and environmental zones, to identify the best policies and their fair and effective implementation to support such payments.

To overcome the current soil policy fragmentation and improve policy cohesiveness in relation to climate, soil protection and health and to enable policy stakeholders to develop, implement and monitor future agricultural soil policies, there is the need to (i) identify synergies and trade-offs between existing policies across different scales to enable strategic policy decision making and support the selection of integrated and cross cutting specific policies for soil protection measures and management practices; (ii) to support scientific knowledge sharing with policy stakeholders and develop new frameworks for future soil policy and eco-scheme development and for carbon accounting initiatives; possibly looking the other way: punish polluters/emitters instead of rewarding clean production; (iii) to provide suitable tools and indicators/guideline values to enable better policy implementation and monitoring at multiple scales. While rewarding organic carbon sequestration in soils receives much attention (e.g., on-going Carbon Farming study led by DG CLIMA[16] and recent LIFE 2020 call on enabling carbon farming[17], solutions for promoting the delivery of ecosystem services by soils are less studied.

Scope: This research should analyse the proposed/perceived solutions (financial and market-based incentives, voluntary and mandatory initiatives) to address the identified socio-economic barriers and levers for increasing carbon sequestration and promoting soil health in agricultural soils, i.e., promoting the delivery of ecosystem services by soils. It should go beyond analysing subsidy-based policies for adapting agricultural practices and systems (e.g., Common Agricultural Policy farm-level payments), to consider rewarding systems based on market solutions and/or sector-specific innovative contract schemes between farmers and agri-food industry and retailers. Such initiatives are best seen as complementary to policy instruments, or substitute if deemed more cost-effective.

Regarding rewarding farmers for SOC storage, the project should consider the following elements for a carbon farming scheme: (i) on-farm C balance and forward-looking calculations of C sequestration over 10-20 years (lifetime of the agreement), based on choices of changing practices and farming systems, (ii) an analysis of risks, responsibilities, and solutions to meet a target and deliver C sequestration and (iii) a payment scheme that covers benefits and returns to farmers in terms of risks and insurance, and defines responsibilities in the event of non-delivery or interruption of agreed services and performance. The study should analyze how rewarding schemes, in particular results- based ones, taking explicitly into account soil properties, interactions between soils and agricultural practices, may be developed for ecosystem services delivered by agricultural soils, including C sequestration. As mentioned above, besides farm-level payments envisioned in the future CAP (Euro Schemes), the project should consider complementary actions to reward farmers, moving away from subsidy-based policies and bringing in more cost-effective market solutions.

This will require to consider different issues regarding: availability of soil properties, their spatial resolution and uncertainties, criteria for indicators selection, baseline, additionality, reversibility and long-term trends, control and verification of results, training and expertise required, accounting of previous work of pioneers, the design of the reward, cost-effectiveness of the payment scheme, agricultural product labelling, social perception from soil up to agri-food chain. These activities will be done in a multi-actor approach, involving stakeholders from all areas of Europe and associating different disciplines (soil scientists, economists and social scientists).

Outputs : An analysis of the strengths and weaknesses of a result-based payment approach for soils and proposals for appropriate payment schemes. Fair and transparent “strengths and weaknesses” analysis of Expected Impacts of subsidy systems and other rewarding schemes, including opinions of diversified stakeholders with an objective of equity. Criteria for indicators selection. Analysis of a result-based payment approach or polluter/emitter pays schemes.

Expected outcomes:

- Development of carbon farming schemes and payment schemes for ecosystem services, adapted to regional conditions.

Expected Impact:

- EJP SOIL EI5: Fostering the uptake of soil management practices which are conducive to climate change adaptation and mitigation

Project Type: Medium size research project (up to 2M€)

Annex 2.3: Topics from which the 3rd internal call and external calls (1 and 2) will be selected (short description)

CM3 - Preserving and managing SOC in peatland and organic soils

This topic is on peatland and organic soils, in particular as these soils contain the highest levels of soil organic carbon and are significant sources of CO_2:

- Improved quantification of C emissions and sequestration potential through conservation of soil C stocks, especially in European organic soils under different hydrological conditions and soil management systems.
- Synthesis of soil management technologies for organic soils and their effects on agricultural production and the economy, the environment and climate change mitigation and adaptation.
- New technologies and management methods that minimize total GHG emissions from re-wetting organic soils, including paludiculture,[24] and other possible management options to sequester C in organic soils and to provide other ecosystem services (e.g., biodiversity).
- Identifying trajectories to reach the quantitative target proposed by the Mission Board Healthy Soils and Food (area of managed peatlands losing carbon should be reduced by 30-50% in 2030).
- Quantify SOC stocks evolutions, GHG emissions in waterlogged, drained or undrained, mineral soils to reflect conditions of the pedoclimatic zones concerned in current and future climates (e.g., drought and warming).

CM4 - Understanding SOC sequestration

Define upper limits for SOC stabilization (for EJP SOIL external call)

Stable C pools are thought to be protected from decomposition by binding to mineral surfaces or locking up in small protective pore systems. It has been hypothesized that there is a maximum amount of C that specific soil can stabilize has been termed “carbon capacity or saturation”.

- What is the C sequestration potential in stable forms of organic matter of different soil types and how can this potential be determined?
- How can stable C in soils be quantified and is this amount really limited by organo-mineral interactions?
- How to determine if a given soil is near a saturation point, since it may pose risks to the permanence of soil C sequestration and may help identify where the potentials to sequester stable carbon really are and how to use available organic amendments effectively.
- Furthermore, the reactive surfaces in a topsoil and so the level of saturation can be considered fixed, but it is possible to alter these surface areas through appropriate soil management?

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[24] The practice of crop production on wet soils, predominantly occurring on peatlands.

Processes explaining the persistence of SOC (for EJP SOIL external call?)

The current hypothesis is that organic C preservation is the result of the interplay between mineralogical and microbiological processes.

- Minerals actively preserve organic C though physical and chemical protection imparting chemical stability, decreasing organic C decomposition susceptibility by microorganisms. In addition, location of organic matter in soils in smaller pore systems may limit their accessibility to further processing and decomposition. Recent results show that organic C processed by soil microorganisms is more persistent in soils than is microbially processed organic matter added to soils. The related hypotheses need to be tested: it may be because microorganism digested organic C is more chemically stable, or more chemically reactive towards minerals, and thus more amenable to mineralogical preservation processes. Therefore, the input of C adjacent to reactive surfaces (e.g., through roots or leaching) results in greater C storage than input onto the top of the soil (e.g., leaf litter or manure).

Persistence of SOC in the subsoil (for EJP SOIL external call?)

The current hypothesis that the persistence of organic matter in deep soil layers is governed by soil microbial activity needs to be tested.

- The mean residence time the subsoil carbon is often larger than that of the organic C in the topsoil, and the proportion of older organic C increases with depth. It can be hypothesized that deep SOC is stabilized via the same processes at play in the topsoil, and that deep SOC is not more chemically resistant to decomposition than topsoil organic C. Rather, that organic C persistence in deep soils would result from the separation from microbes, substrate and the atmosphere.

CM6 - Stochiometry of C-N-P as drivers for SOC storage and persistence and GHG emissions

- How do C-to-N-to-P ratios affect the persistence of organic matter and how do they constrain the SOC storage? How to solve the dilemma between conserve organic matter and profit from its decay for soil fertility?
- How does these ratios affect the N_2O to SOC sequestration balance?
- The dynamics and interactions of SOC and greenhouse gases (primarily CO_2, N_2O, and CH_4) emissions are different across ecosystems and climatic zones. For national inventories, GHG emissions are often estimated using the IPCC Tier approaches. These do not account for the complex dynamics underpinning SOM turnover. Three questions are posed: Could N_2O emissions in agricultural soils be primarily estimated from N inputs with low C:N ratio biomass? Could C input to soil be estimated from NPP and the fraction of this returning to soils? Could the mean residence time of C in soil organic matter vary under given climate and soil physico-chemical conditions, due to increased turnover (priming effect) whenever the balance of C to N inputs to soils is high?

CM7 - Components of a European SOC MRV platform

A consensus has recently been reached on the need for hybrid SOC MRV platforms, combining the use of, i) spatial data of climate, soil and agricultural activity, ii) long-term experiments, iii) soil monitoring systems, and iv) remote sensing with modelling. There is a need to develop such a platform in Europe in particular by:

- Identifying benchmark sites, i.e. long-term experiments or paired plots with contrasted management to test the models used, for the main pedoclimatic, production systems and management options. The relevance of EJP SOIL long-term experiments should be examined in that perspective.
- Developing the measurement of SOC contents and entry variables for models: (i) activity measurements (e.g., bare soil, residues returns), and (ii) biomass estimates using remote sensing.
- Increasing the use of spectroscopy methods for measuring SOC contents (in the lab or in the field).
- Improving SOC models for MRV platforms (e.g., model inter-comparisons, testing approaches with ensemble modelling, adequate model initializations measuring SOC kinetic pool sizes with fractionation or other methods).
- Testing models on soil monitoring networks results (National monitoring networks, LUCAS).
- Analysing uncertainty and biases associated with different MRV systems (e.g., related to the source of the activity data and models used).

In addition, simple C balance model or platforms to support and assist farmers and advisory services in setting up farm-level C balances, based on the implementation of practices and measures to enhance C sequestration to monitor and report on performance should be built-up.

CA2 - Identifying viable farm-level incremental adaptation options, related to soil management, to respond to water impacts of climate change on agricultural soils: droughts, heavy rains and waterlogging.

Creating a Europe wide overview of water related impacts (drought, flooding), extreme events and erosion of current and predicted climate change. Establish EU farm networks to implement and learn different soil management measures with farmers. A possible approach may be to identify geographic hotspots and vulnerable cropping and farming systems. For the top 3-5 hotspots and top 3-5 vulnerable cropping systems, identify cost-effective adaptation options. The project should associate biophysical expertise and economic expertise.

- Evaluate methods for adapting to water impacts of climate change without compromising agricultural soil health:
- Methods to better identify soil physical and chemical limitations to root and crop growth at field and landscape scale.

- New ways to use stable organic amendments to ameliorate soil physical and chemical stresses to the crop root systems limiting rooting depth and crop productivity and/or to use new cropping systems much more adapted to soil constraints.
- Increased water resources through recycling (water reuse, reservoirs,…) and increased crop water uptake efficiency.
- New irrigation management (e.g., using sensors to observe soil dryness and anticipate drought, using models).
- Measures to prevent soil erosion by using cover crops, improving soil structure, increasing soil infiltrability and in other ways.
- Insight in the financial resilience and relative competitiveness of farming systems and cropping systems across Europe and the potential climate change induced shift in resilience and competitiveness. Identify options in soil-crop management to adapt to adverse effects and possibly exploit positive results.

CA3 Consequences of climate change and potential adaptation options on C, N and P cycling and potential adaptation options for managing them

- Inventory of current soil management options that support and enhance nutrient retention, nutrient regulation and carbon sequestration in the context of climate change for European conditions.
- To what extent current soil management aiming at maintaining or enhancing the nutrient retention function in the different agro-ecological zones in Europe are still valid for the near future?
- How do changes in temperature and rainfall intensity and patterns impact the C, N and P cycling in different soil-crop combinations and European pedoclimatic conditions?
- How to exploit potential benefits of increasing soil carbon for adaptation to climate change without compromising yield and environmental goals?
- Provide practical solutions to adjust management to achieve a positive impact on crop production and maintain environmental standards as defined in the nitrate directive and water framework directive.

SP4 - Innovative technologies for diversified cropping and site-specific sustainable soil management

This topic considers the use of novel advanced technologies for diversified cropping (strip cropping, pixel farming) and site-specific soil management with the overall aim of improving soil health, productivity and sustainability. Novel technologies include digital and site-specific cropping, drones and sensors, and the use of autonomous robots.

- Collect and synthesize knowledge on the successful and unsuccessful use of novel advanced technologies in relation to diversified cropping (e.g., strip cropping and pixel farming) and site-specific soil management (tillage and traffic, fertilization, weed and pest control, irrigation).
- Quantify impacts of applying novel advanced technologies on soil health, productivity and overall sustainability in existing and new field experiments.

- Evaluate the potentials and limitations of using novel advanced technologies for climate-smart sustainable soil management for different pedoclimatic zones and cropping systems.

SE1 - Site-specific landscape analysis to design Nature-Based Solutions

Develop and assess site-specific (farm scale) Nature-Based Solutions* for healthy agricultural soils, N from a biophysical and a socio-economic point of view.

1. Implications:
   - What are the off-site effects of non-sustainable soil management and off-site benefits of climate-smart sustainable soil management?

2. Solutions:
   - Which scientific solutions are needed to combat climate change and foster resilience? Potential solutions to be assessed: erosion protection measures, crop diversification, organic amendments, biodiversity as a management tool, agroforestry, integrated pest management
3. Nature-Based Solutions:
   - Actions for societal challenges that are inspired by processes and functioning of nature. By developing and implementing solutions that are supported by nature, resilience is achieved while producing societal, environmental, and economic benefits.

SE3 - Soil restoration: options and indicators for land degradation neutrality

Soil restoration research should establish technological options as well as nature-based solutions and their potential for restoring degraded land and soil. Two major contexts may be considered:

- Restoring soil in urban and peri-urban areas for sustainable agricultural production: Unsealing soils (i.e. suppressing the impermeable material covering soil) in urban and peri-urban areas:
  - Gather knowledge and experience on how to successfully unseal soils for urban or peri-urban agricultural use.
  - Assess the soil's potential for sustainable production and other ecosystem services after restoration taking into account potential soil contamination.
- Restoring degraded soils in agricultural land: assess potential of available solutions such as long-term reduced soil physical disturbance, deep-rooting crops, agroforestry systems, high density grazing systems, diversified landscapes.

In addition, to assess restoration efforts using the SDG15.3 target 'land degradation neutrality' a common tool needs to be developed, that is suitable for the European context; including indicators to assess soil health regarding the natural capital in soils and the provision of ecosystem goods and services.

SE5 - understanding the effects of climate change on soils salinisation: understanding the processes and improving cropping systems (with specific attention for irrigation) under current and future climate

Agricultural soil salinization is a major soil threat in southern and eastern Europe, and under the predicted climate change it is likely to become also a more important issue in other regions of Europe. However, the process of salinization and how it relates to irrigation schemes and possible mitigation, adaptation and restoration strategies need to be investigated:

Process understanding:

- Understand the role of organic matter in salinization development/mitigation;
- Understand the role of changes of agricultural systems, specifically related to irrigation implementation for the availability of green water for crops, for the current and predicted climate
- Trade-offs of different irrigation schemes for salinization risks.

Mitigation/adaption/restoration options:

- Irrigation optimization, options, alternatives: trade-off assessment for multiple ecosystem services
- Assess and develop strategies for trace element contamination due to salinization
- Assess links between soil organic matter content and salinization risk and identify optimum soil organic matter status.
- Develop farm systems in saline soils: potential of saline crops, salinization management.

SE6 - Soil futures: scenario modelling for assessing the potential of climate-smart sustainable soil management to provide multiple ecosystem services.

This synthesising project will focus on bringing information together on the potential of soils to provide a wide range of ecosystem services such as sequester more carbon for climate change mitigation, adapt cropping systems to climate change, sustainably produce food and biomass, regulate water quantity and quality…

- The project will use models and approaches, including those utilised or developed in EJP SOIL projects (e.g., models to predict soil carbon sequestration) to evaluate the provision of ecosystem services by agricultural soils, among which agricultural production and climate change mitigation, under climate-smart sustainable soil management options.
- Scenarios considered will be climate change scenarios (based on the IPCC scenarios), scenarios for agricultural production (e.g., extensification, dietary changes), land-use change scenarios (including urbanization), socio-economic changes and policy framework induced changes (e.g., Farm to Fork strategy target of 25% EU farmland becoming organically managed by 2050) to deliver these ecosystem services.
- The outputs of these scenarios will be compared with the quantitative target proposed by the Mission Board on Healthy Soils and Food (e.g., current C losses in farmlands should be reversed to an increase by 0.1-0.4% per year).

NET1 - Citizen science (including farmers) protocols to support science-based soil knowledge and site-specific policy applications.

For site-specific transitions, soil policy needs to be adapted to local conditions. National and regional soil information is often insufficient to guide soil policy and soil management at local scales. Therefore, citizens (farmers, urban people etc.) involved in food production and soil management require better knowledge of their soils capacity to perform different functions to understand and apply public policies related to soil. Citizen science is an interface between these two issues. The soil is currently a fuzzy object for society, and therefore an interdisciplinary and transdisciplinary object for research. Such citizen science initiatives, developing across Europe, can overcome this apparent complexity, and should be shared to enrich one another & coordinated to support policy objectives. In most ongoing citizen science initiatives, scientists are involved with other partners. Mapping these initiatives should be the first step of the project (how, how, where,…), followed by their coordination across Europe. The data citizen science initiatives generate is expected to improve other soil databases, citizen awareness and knowledge on soils, and finally a better understanding of agricultural soil in public policies.

DATA 2 - Feasibility of the mapping of soil management practices through remote sensing.

Testing (calibration, validation) of existing procedures, retrieved through a literature review.

Reasoning, elaboration and testing of promising new procedures to assess spatial information on soil management practices through remote sensing. Soil management practices can include cropping systems, tillage systems, and land restoration practices.

Validation of mapped data of soil management could be performed in collaboration with JRC/ESDAC and their datasets.

The result of such a project could be used for instance in mapping and or as an input information for modelling of soil carbon sequestration potential or other ecosystem services.

DATA 3 - Estimation of soil physical degradation due to climate change through remote and/or proximal sensing

Soil physical degradation due to climate change.

Current field measurements of compaction are time-consuming and costly. Covering the small-scale variation of soil compaction, which often even larger than the large-scale variation, is therefore difficult. Using multiple sources of data including proximal and remote sensing measurements could be a way to identify areas with a high risk or probability for soil compaction and actual compaction. The project should assess the feasibility of the techniques in different land uses and climatic zones and expected accuracy

DATA 4 - Comparative analysis and harmonization of soil data analysed with different (ISO) standards.

Soil properties are analysed in the lab following different (ISO and other) standards, which is a strong impediment for compiled soil data sharing and use inside common research activities. Work on the harmonization of methods is therefore needed and is currently ongoing inside the Global Soil Partnership (Pillar 5,) and Global Soil Laboratory Network (GLOSOLAN) to standardize laboratory standard operating procedures and make an inventory of needs for harmonization between methods.

The research will consist in the stocktaking, testing, and/or elaboration of agreed pedotransfer functions for the harmonization of soil analyses to common standards. It will be performed at least for the main soil properties as defined by Global Soil Map specifications (2015): soil organic carbon, pH, texture, cation exchange capacity and exchangeable bases, bulk density, electrical conductivity, and available water capacity

AD1 - Regional Living Labs and lighthouses for healthy soils and sustainable farms

To reach sustainable soil management fostering sustainable farm management and understanding what is needed for farmers to adapt sustainable soil management practices is key. The European Union launched in 2020 the Farm to Fork Strategy: for a fair, healthy and environmentally friendly food system. To reach this goal, the food system needs to transform to a truly sustainable system, from a soil, water and biodiversity point of view, as well as a socio-economic point of view.

The approach in this project will be to work with regional Living Labs (a testing area for ideas that help accelerate the development of sustainable, future-proof solutions) and lighthouses (examples for sustainable soil management in a region). In each participating country running Living Labs will be asked to participate and lighthouses will be searched for by connecting to specific ‘local champions’ that are successfully implementing climate-smart sustainable soil management. The aim of this project is to:

- Assess the boundary conditions in the envisioned Farm to Fork food system for a sustainable farm including soil and water limitations, agronomical limitations, and economic and social limitations such as agricultural products discarded for being less than perfect; price on the market too low to harvest, subsidies applications etc.
- Assess pros and cons of sustainable soil management strategies in the participating regions
- Assess region-specific sets of best practices that can be further developed together with farmers in a co-innovation process

AD2 - Tools for evaluating and communicating soil quality for healthy soils and sustainable farms

To foster adoption of climate-smart sustainable agricultural soil management by farmers it is important that farmers (and other stakeholders) and scientists speak the same language. Discussing soil quality/soil health with farmers and other stakeholders leads often to Babylonian confusions. Therefore, two essential tool categories are needed:

Tools needed for evaluating soil health:

- (Re)developed tools for farmers to assess soil quality;
- Validated and standardised measurement methods;
- Clear target and reference values;
- Multi-criteria planning and evaluation tools for soil health that take into account the socio-economic aspects at farm level through the evaluation of soil properties, soil biodiversity, soil functions and linked ecosystem services;
- Tools for assessing trade-offs associated with selected soil management strategies at relevant spatial scales using relevant case studies for different EU zones, including grasslands and organic soils.

Tools needed for communication :

- A clear framework for Europe with a uniform comprehensible 'language' to set the basis for soil quality and soil health assessments.

These tools might be co-created with the farming sector, in the spirit of participatory research.

AD3 - Soil-specific guidelines and decision support tools with a focus on soil organic matter and climate change effects

There is a need to develop and/or update soil-specific guidelines and decision support tools to assist advisers and subsequently farmers in the decision-making process on various aspects of soil management. The guidelines and decision support tools need to be tailored to regional conditions and farmers' needs. However, the development process and knowledge base for the guidelines and tools can be generic. There is especially a need for guidelines and decision support tools for water storage and purification, soil organic matter sequestration, cycling and regulation and provision and cycling of nutrients including nutrient use efficiency, i.e. a focus on other soil functions than primary production alone. The guidelines and decision support tool should assess the current and potential supply of the different soil functions by agricultural land.

- For guidelines, new approaches are in development, which can be shared and harmonized over Europe and tailored to the specific regional conditions.
- For decision support tools, integration of several soil management aspects in one tool, without comprising the quality of it, is desired.

This project should deliver, next to a collection of applicable tools for various subjects and regions in Europe, also a procedure to develop good quality tools.

POL1 - Increasing soil protection and soil health within public policy

Increased visibility and value placed on soils by citizens and policy stakeholders is needed so that the conservation, sustainable management and environmental impacts of agricultural soils (in rural and urban areas) are considered and prioritized for soil-related policy creation and implementation.

Research that examines how soil and agricultural soil management issues are portrayed and treated on societal and political agendas is required to improve the demand and prioritization of soil health related issues in EU and national policy.

Research will analyse the mechanisms for promotion of new policies, measures and initiatives aiming to improve agricultural soil health and tackle agricultural soil issues and the associated tensions and controversies.

POL 3 - Support for soil and agro-ecological transitions across territories and agri-food chains for a circular bioeconomy

Despite its crucial ecological importance, soil remains broadly understood as an inert background for biological and social existence at its surface. However, soils are currently increasingly recruited and enrolled in a range of policies, projects and promises of ecological, energetic, climatic and agricultural transitions. These transitions require social-science investigation and scrutiny. Soil biodiversity and its functions could play a major role between food production, ecological and social issues. Research is needed to build understanding and address barriers for the adoption of climate-smart and sustainable soil management, including the role of decision support tools in farmers decision-making.

Research should examine the contemporary reinvestments of soils in a context of social and ecological transitions to produce critical knowledge to support shifts towards knowing and managing soil resources more holistically in innovative agri-food chains and territories, leading to agroecology and/or circular bioeconomy. Initiatives aiming for biodiverse, healthy soils and landscapes are being developed in territories (communities, large cities) and in agro-food chains (labels.), and are key to sustain a transition towards the circular bioeconomy and/or agroecology.

The objective of the research is to analyse how soils are, and could be, taken into account in such initiatives and how they can be leveraged for science to policy interaction and translation. Challenges that withhold accomplishing these initiatives should be assessed and appropriate context-specific solutions developed, in relation with public policies.

Research should focus on analysing existing initiatives and developing EU region-specific scenarios integrating healthy soils and landscapes for building a circular bioeconomy and/or agro-ecological transition:

- Resource management optimization, closing nutrient and energy circles, integration of urban composts and green wastes recirculation;
- Economically viable and socially acceptable solutions that are sustainable beyond the agricultural sector;
- Multi-use land management;
- Integration with biodiversity strategy 2030, the farm to fork strategy and the european climate law.

POL4 - New social and economic methods & scenarios for policy development

Generally, it is important to support a transition from activity to performance-based schemes as these are more efficient. For example, a key challenge to increase soil C is that changes are so gradual that it is difficult to use direct observations as a basis for regulation, particularly for development of performance-based payment schemes. Research will identify co-innovation by different stakeholders, and evaluate the benefits of different potential instruments such as public-private partnerships, market /industry led schemes, farmer led schemes, voluntary initiatives etc. to foster the uptake of soil management practices that are conducive to climate change mitigation and adaptation and can support the interface between science-policy.

POL5 - Tools and models for supporting integrated soil policy

The effect of climate change mitigation and adaptation measures identified and promoted may not be fully evaluated for their synergistic or antagonistic consequences on other sustainable soil management targets (water quality or biodiversity etc.) and soil ecosystem services. Additionally, analysis to-date does not elucidate mitigation efficacy across different scales, farm typologies and biophysical settings. Hence, there is a need to improve the knowledge and understanding of specific mitigation costs and mitigation capacities across different scales and settings.

Research is required to address the synergies, antagonisms and cost/benefit ratios between different mitigation strategies for EJP SOIL domain challenges by testing scenarios within more integrated models (agriculture, climate, soil, and economy). Using / developing integrated models that couple existing models and the expertise behind is needed. Integrating analysis for multiple soil targets will provide new insights and knowledge to support effective soil policy and selection of more cross-cutting measures to be included in eco-schemes and incentives in future.