








European agricultural soil management: Towards climate-smart and sustainability, knowledge needs and research approaches

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Abstract

Current soil- and land degradation seriously challenge our societies; it contributes to climate change, loss of biodiversity and loss of agricultural productions. Yet, soils are also seen as a major part of the solution, if maintained or restored to provide ecosystem services. Climate-smart sustainable management of soils can provide options for soil health maintenance and restoration. In the European Union, the resource management and sustainability challenge are addressed in the Green Deal that, among other goals, aspires towards a healthy climate-resilient agricultural sector that will produce sufficient products without damaging ecosystems and contribute to better biodiversity and mitigate climate change. The European Joint Programme (EJP) SOIL was set up to contribute to these goals by developing knowledge, tools and an integrated research community to foster climate-smart sustainable agricultural soil management that provides a diversity of ecosystem service, such as adapting to and mitigating climate change, allowing sustainable food production, and sustaining soil biodiversity. This paper provides an overview of the potential of climate-smart sustainable soil management research to the targets of the Green Deal that are related to soils most directly. The EJP SOIL EU-wide consultation (interviews and questionnaires) and literature analysis (national and international reports and papers) done in the first year (2020–2021) generated a wealth of data. This data showed that there are specific manners to do research that are essential for it to be effective and efficient and that can actively contribute to the Green Deal targets. We concluded that research needs to be: (i) interdisciplinary, (ii) long-term, (iii) multi-scaled, from plot to landscape, (iv) evaluating trade-offs of selected management options for ecosystem services and (v) co-constructed with key stakeholders. Research on climate-smart sustainable soil management should be developed (1) on plot scale when mobilizing soil processes and on landscape scale when addressing sediment and water connectivity and biodiversity management; and (2)

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address the enabling conditions through good governance, social acceptance and viable economic conditions.

KEYWORDS

(bio) diverse landscapes, science–policy interface, soil health, soil information, soil management knowledge, Sustainable Development Goals

1 | INTRODUCTION

The challenges related to sustainable resource management are well described in several recent publications such as the ones by the Intergovernmental Platform on Biodiversity and Ecosystem services (IPBES, 2019), Intergovernmental Technical Panel on Soils (FAO and ITPS, 2015), European Court of Auditors (ECA, 2018) and Intergovernmental Panel on Climate Change (IPCC, 2019). They all stress that current soil- and land degradation is seriously challenging our societies, yet they also state that soils can be a major part of the solution for addressing these challenges.

In Europe, the resource management and sustainability challenges are addressed in the European Green Deal (hereafter labelled ‘Green Deal’) launched by the European Commission in 2019 (European Commission, 2019) (https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF).

Together with the wider aspiration to become the first climate-neutral continent of the world, the Green Deal aims for a healthy agricultural sector that will produce sufficient products without damaging ecosystems (Hossain et al., 2020; Panagos et al., 2018). This requires a big shift in agricultural practices and supporting policies that have been designed around the use of agro-chemicals, heavy machinery and industrialization. Because of this, modern agricultural practices often contradict the Green Deal aspirations, contributing to continued soil degradation. While the Green Deal proposes to halt degradation and restore ecosystems, the intensification and industrialization of the agricultural sector are still ongoing, with ever larger scale mono-cropping and use of pesticides, heavy machinery and herbicides and excessive use of (synthetic and organic) fertilizers (Hossain et al., 2020; Panagos et al., 2018). The Green Deal is not a single strategy, but rather an overarching framework for a series of environmental objectives (Figure 1), supported by a set of interconnected strategies, each associated with very ambitious quantitative targets. Three of the strategies are outlined here.

The European Climate Law requires greenhouse gas (GHG) emission neutrality within the EU by 2050 at the latest (European Commission, 2018). The Land Use, Land Use-change and Forestry (LULUCF) regulation has

Highlights

- Research on climate-smart sustainable agricultural management is key to the Green Deal soil related objectives.
- Soil research needs to be transformed to include: interdisciplinarity, long-term experiments, at multi-scale.
- Soil research should pay attention to trade-offs on management options and include multi-actor approaches.
- More research needed on enabling socio-economic for the adoption of climate-smart sustainable soil management.

been amended, setting a new objective for achieving climate neutrality in the entire land sector, earlier, by 2035 (European Commission, 2021, 2021a). This means that carbon removals in terrestrial ecosystems should balance the GHG emissions from all land, livestock and fertilizer use. This will require an increase of net carbon removals by 20% and a decrease of non-CO₂ emissions in the agricultural sector by 20% (European Commission, 2021b).

The Green Deal’s Biodiversity strategy ‘Bringing nature back into our lives’ specifically addresses the value of ecosystems and biodiversity and describes a plan to protect nature and reverse the degradation of ecosystems. The Biodiversity Strategy states that by 2030, the current decline in biodiversity should have been curbed and on the road to recovery, and that 30% of land and sea areas in Europe should be under environmental protection (European Commission, 2020). It also aims to bring back 10% of agricultural area under high diversity landscape features, and plant more than three billion trees.

The Green Deal Farm to Fork Strategy (‘a fair, healthy and environmental friendly food system’) brings together elements from other Green Deal strategies and as such constitutes a cornerstone of EU’s agri-food policies. It notably aims to reduce the use of pesticides by 50%; reduce nutrient losses by 50% and fertilizer use by 20%; reduce antimicrobial use in farmed animals by 50%;

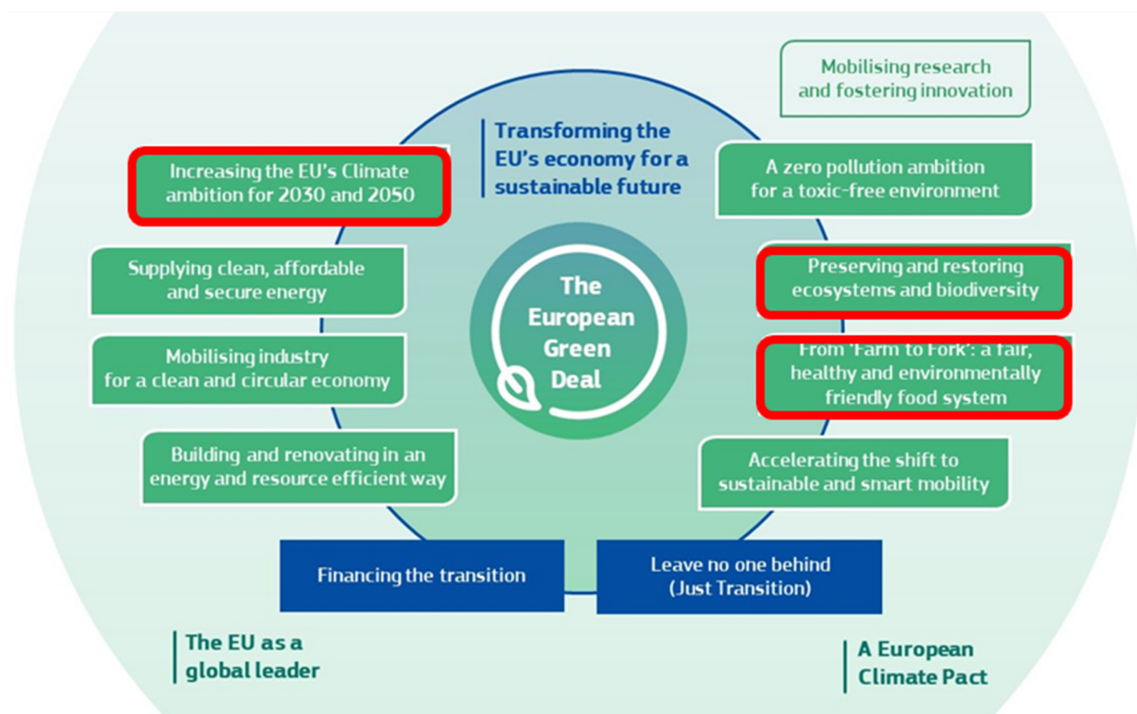


FIGURE 1 The Green Deal objectives (European Commission, 2019). Red delineation indicates the objectives that strongly benefit from sustainable soil management.

and have at least 25% of the EU's agricultural land under organic farming by 2030 (European Commission, 2019). This combined with other challenges like the expected 70% increase of global food demand by 2050 (FAO, 2009), the Zero Hunger ambition of the Sustainable Development Goals (SDGs) (UN, 2015) and the increasing demand for biomass for bioenergy and bio-based industrial production, demonstrates the need for a transition in the agricultural sector in Europe and beyond. The new CAP is aimed to support the Farm to Fork Strategy on the ground.

Even if explicitly mentioned only in the Farm to Fork Strategy and Zero pollution action plan, soils are clearly concerned by the Green Deal, in two ways (Montanarella & Panagos, 2021). First, soils will be impacted by measures implemented to respond to the Green Deal objectives, such as that of reducing GHG emissions in the LULUCF sector, which will require reducing GHG emissions from soils. Halting biodiversity loss will benefit soil biodiversity, and reducing the use of pesticides will reduce soil contamination. Second, sustainable management of soils is key to progressing towards the goals of the Green Deal. As clearly defined by FAO (FAO, 2017) 'soil management is sustainable if the supporting, provisioning, regulating, and cultural services provided by soil are maintained or enhanced without significantly impairing either the soil functions that enable those services or biodiversity'. Since the launch of the EU Green Deal, the commission set the EU Soil

Strategy (2021) and the Mission 'A Soil Deal for Europe', which directly focus on soils. What are the research needs upstream of these policy frameworks and ambitious targets?

Soils play a major role in addressing a broad range of societal issues of our time, and agricultural soils are, on the one hand mostly degraded in Europe (EEA, 2020), and on the other hand key to the Green Deal objectives' achievement. In this perspective, the European Commission launched a European Joint research Programme on agricultural soils, the European Joint Programme (EJP) SOIL (www.ejpsoil.eu), with as a key objective: 'developing knowledge, tools and an integrated research community to foster climate-smart sustainable agricultural soil management that adapts to and mitigates climate change, allows sustainable food production, sustains soil biodiversity and soil functions and ecosystem services'. What is aimed at for agricultural soils is both sustainable soil management (as defined previously, FAO, 2017) and climate-smart soil management. The FAO defines climate-smart agriculture as aiming to sustainably increasing agricultural productivity and incomes, adapting and building resilience to climate change, and reducing and/or removing greenhouse gas emissions, where possible (<https://www.fao.org/climate-smart-agriculture/en/>). Climate-smart management of soils can then be understood as soil management that improves its capacity to adapt to climate change and to

reduce greenhouse gases emissions or remove carbon from the atmosphere.

To contribute to developing an integrated research community, the EJP SOIL fosters stakeholder consultation. In the first year of the programme (2020–2021), the EJP SOIL aimed to develop its research roadmap. To obtain a vision of the current state-of-affairs regarding climate-smart sustainable management of agricultural soil, stocktakes have been undertaken, in which an extensive process of consultation among European stakeholders in 24 countries, together with a limited review of grey and ISI literature was done. The data of the stocktakes were analysed and placed in the perspective of the Green Deal targets related to soils. From this analysis, research needs and promising research approaches were extracted to feed the EJP SOIL research roadmap.

Therefore, this paper aims to give direction to the research needed to support the transition to climate-smart and sustainable management of agricultural soils, both in terms of research topics answering to knowledge needs on processes and on management options and research approaches. Specific attention is given to how different soil management options can contribute to the goals of the Green Deal related to climate-smart sustainable agricultural soil management (Climate Action, Biodiversity and Farm to Fork strategies). The role of soil health and healthy and (bio)diverse landscapes (landscapes rich in biodiversity and landscape elements) to achieve these goals are defined, explained and highlighted. The paper ends with a set of research priorities to assist strategic decision-making in science, policy and implementation issues as well as contributing to creating an agricultural environment that will enable farmers to once again be and be seen by the public as the stewards of land and soil resources.

2 | MATERIALS AND METHODS

2.1 | Stakeholder consultation

In this paper, the data acquired in the EJP SOIL (www.ejpsoil.eu) was used. In the first year (2020–2021), an EU-wide inventory of knowledge needs on climate-smart agricultural soil management was made. In the 24 EU countries participating in EJP SOIL, a thorough national stakeholder consultation was performed. We established in each country an ‘EJP SOIL National Hub’, that is, a group of stakeholders comprising representatives from main soil stakeholder groups including academics, policy makers, NGO's and farmer organizations or farmers, with the mission of providing input and feedback to the EJP SOIL programme and to voice national specificities and

needs. Through this process, a total of >300 stakeholders were consulted. A three-step approach was followed to identify the knowledge needs from across Europe:

1. the stakeholders were asked for their *aspirational targets* that identified future soil ecosystem services aspirations at regional, national and European level. This included the identification of the future needs for soil functions and ecosystem services and of the main drivers affecting them.
2. *the knowledge availability and use* were investigated (i) in a review and stocktaking of current agricultural soil-related research activities, soil-based policies and scientific literature and (ii) an assessment of the availability and use of the knowledge, via a consultation of the National Hubs stakeholders.
3. the *barriers and opportunities* to reach the aspirational targets were identified, again via stakeholder consultation.

For this, inventory questionnaires were sent out in each country and interviews were held with key representatives of the National Hubs. The findings of these surveys were reported in three reports of EJP SOIL (D2.5, D2.6, D2.7 and D2.8, accessible on www.ejpsoil.eu). Through this consultation, the existing knowledge needs were identified according to the EJP SOIL Knowledge framework (reported in a deliverable 2.4 of the EJP SOIL: Keesstra et al., 2020), hence needs for knowledge development (new research, knowledge synthesis), for knowledge sharing and transfer, knowledge harmonization and knowledge application across partner organizations and member states. In addition, *five EU-wide stocktakes* were completed: (i) The impacts of sustainable soil management practices (Paz et al., 2021); (ii) Soil quality indicators and associated decision support tools, including Information and Communication Technology (ICT) (Pavlů et al., 2021) tools; (iii) Estimates of achievable soil carbon sequestration on agricultural land in the EU (Rodrigues, Fohrafellner, et al., 2021; Rodrigues, Hardy, et al., 2021); (iv) Inventory of the use of models for accounting and policy support (Astover et al., 2021); and (v) Stocktake study and recommendations for harmonizing methodologies for fertilization guidelines across regions (Higgins et al., 2021).

The results of the Europe wide consultation are described in four reports of EJP SOIL: D2.5 by Ruyschaert et al. (2020); D2.6 by Munkholm and Zechmeister-Boltenstern (2021); D2.7 by Thorsøe et al. (2021) and D2.8 by Farina et al. (2021), which can be found at www.ejpsoil.eu. D2.7 formed the basis for the manuscript of Thorsoe et al. (submitted to the same *EJSS* special issue) and D2.8 the basis for the paper by Vanino et al. (2023).

From this inventory, in combination with a review of selected literature, a roadmap was developed for the work to be done in the framework of this research programme. This paper used the part of the collected data that was related to knowledge development.

2.2 | The Green Deal as a guide

We related the knowledge needs that emerged from the stakeholder consultation to the objectives of three Green Deal strategies (Figure 1). Our work also touched upon elements in other objectives such as the one for 'A zero pollution ambition for a toxic free environment', but this was not included in this paper.

2.3 | Scales to consider: Plot scale, (bio) diverse landscapes and socio-economic systems

Complementary scales can, and need to be considered when dealing with climate-smart sustainable management of soils and its contribution to the Green Deal: (i) soil health at the plot scale, (ii) (bio)diverse landscapes and (iii) the socio-economic system.

Soil Health has been defined by Veerman et al. (2020) as 'the capacity of soils to contribute to ecosystem services in line with the Sustainable Development Goals'. Indeed, soils are not only a set of individual characteristics, but are complex adaptive systems functioning as a part of the landscape, and soils provide ecosystem services on different temporal and spatial scales.

Soil health is most often assessed at the local scale, that is, the plot scale. However, considering larger spatial scales are essential as soils are interconnected through water bodies and a diversity of fluxes in the landscape. Accordingly, the Farm to Fork Strategy aims to bring back at least 10% of agricultural areas under high diversity landscape elements by 2030. It is also important to consider how and at which scale soils are connected with people and social and political organizations. This makes the landscape and regional perspective essential to consider synergies and trade-offs of implemented measures and adds the socio-economic perspectives to agricultural soil management.

2.4 | Linking soil functions with land management

To structure the stakeholders consultation and the emerging knowledge needs list, we developed a conceptual

framework (Figure 2) that illustrates the multiple links between elements of climate-smart sustainable agricultural soil management and soil challenges, as well as with the societal goals.

Seven agricultural *land management categories* were identified. Within these categories, farmers make choices, implementing management options. Items of climate-smart sustainable soil management options were derived from FAO voluntary guidelines (FAO, 2017). Policies can directly interfere with choices that farmers make within the 7 land management categories by mandatory regulation, economic instruments, voluntary approaches and educational/informational instruments.

Soil management affects soil characteristics and its primary functions that will underpin agricultural ecosystem services (Figure 2), possibly contributing to the *Green Deal soil related goals*. To support primary soil functions, several soil challenges must be avoided. The interaction between the soils and management parts of this diagram will enable identifying key research needs and key actions that are essential to optimize the role of soil in providing their ecosystem services to achieve the Green Deal related goals (Figure 2).

3 | RESULTS

Tables 1 and 2 give an overview of the key knowledge gaps that were identified in these reports for soil challenges (Table 1) and soil management (Table 2).

3.1 | Identified research gaps related to soil challenges in agricultural land

The interaction between the soils and management parts of the Figure 2 diagram has been used for identifying key knowledge needs and key actions that are essential to optimize the provision of ecosystem services by soils and hence research needs. There is a need for better understanding these interactions and potential synergies and trade-offs. For this, a more holistic perspective and use of systems thinking when designing solutions are needed (Köhler et al., 2019). In practice, soil challenges are highly interrelated and also connected with wider societal concerns. Consequently, management options and instruments should not be assessed and adopted because of their effect towards only one particular soil challenge, but with a holistic view.

For each of the main soil-related Green Deal elements that we are addressing in this paper, we have identified the knowledge needs in a three-step approach. In the first step (green bar in Figure 3), we have identified research

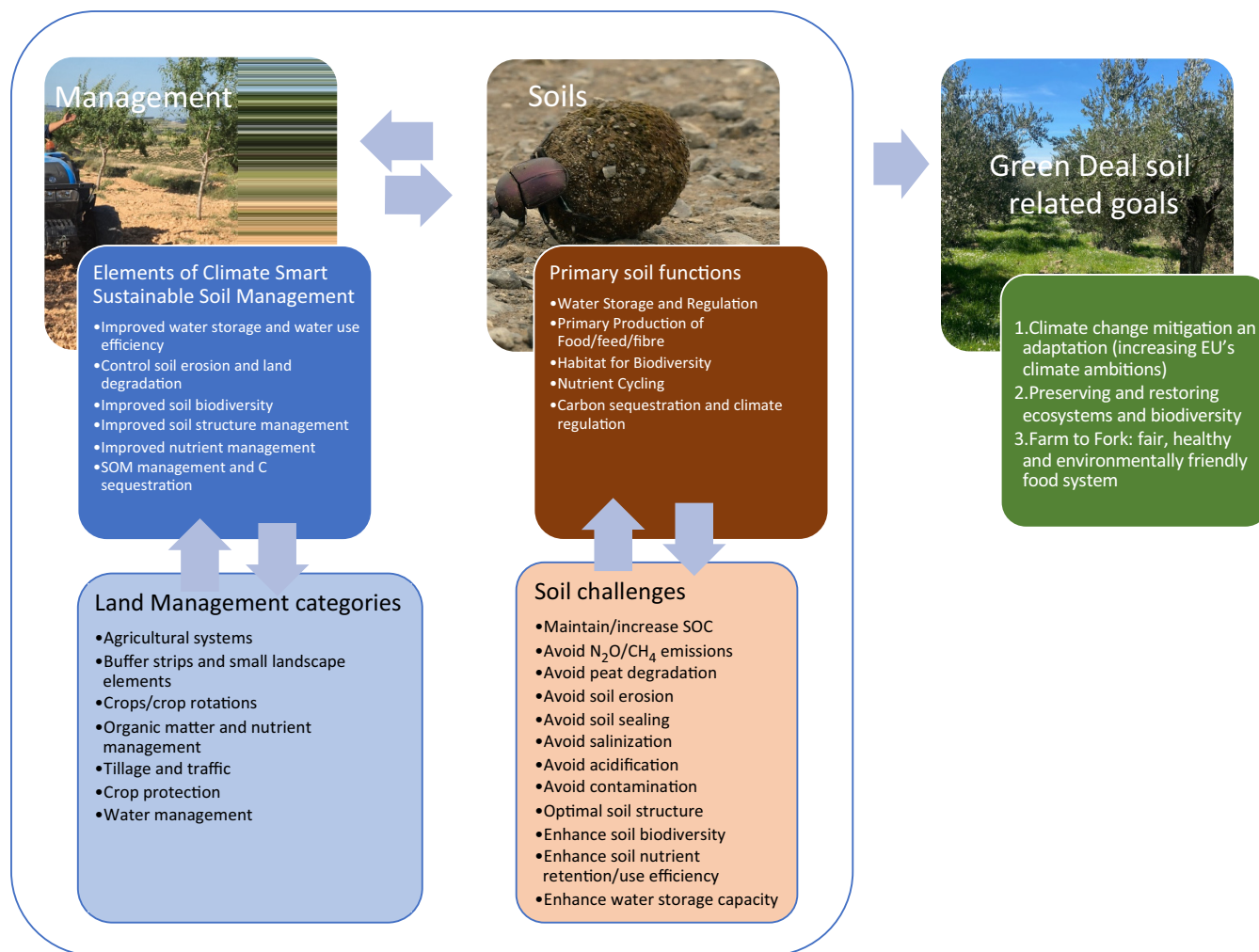


FIGURE 2 Conceptual framework explaining the linkages between the soil functions and the current soil challenges; the land management categories and current climate-smart sustainable soil management options. Implementing adequate soil management options will influence soil functions in a way that will enable the contribution of soils to the achievement of the soil related Green Deal goals. SOM, soil organic matter; SOC, soil organic carbon.

needs that are related to the bio-physical system, at the plot-scale and landscape-scale. In the second step (yellow bar in Figure 3), we focus on solutions, that is, agro-ecological solutions for climate-smart sustainable soil management. The last step (blue bar in Figure 3) looks at the socio-economic dimension that is needed. Here, we address the enabling conditions required for the transitional change needed to achieve the Green Deal goals.

In the next section, the three soil-related goals are discussed along this three-step approach.

3.2 | Green Deal goal climate-change mitigation

As presented in the introduction, the LULUCF sector is expected to achieve climate neutrality by 2035 (EU, 2018),

which is estimated to correspond to a decrease of non-CO₂ emissions in the agricultural sector by 20% and an increase of net carbon removals by 20% (European Commission, 2018).

Soils are key to these objectives, being responsible for non-CO₂ emissions (N₂O and CH₄). Soils are estimated to be responsible for 36% of EU N₂O emissions (ECA, 2021). Soils also represent the largest terrestrial reservoir of organic carbon (Le Quéré et al., 2018). 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) and continue losing C in many European locations. While it is established that the technical, economic and achievable potentials for soil organic carbon (SOC) storage are limited and are well below the need in terms of climate change mitigation, storing additional C in soils remains a key option to be implemented widely

TABLE 1 Identified knowledge gaps related to soil processes in relation to soil challenges collected during the European Joint Programme SOIL stakeholder consultation.

Enhance water storage	<ul style="list-style-type: none"> Assessment of water storage capacity at the root zone level Influence of agroecological practices and systems on soil infiltration capacity Influence of agroecological practices and systems on blue- and green water trade-offs Influence of agroecological practices and systems on water storage capacity for different soil types and SOC contents Understanding of the dynamics of the hydrological properties of the soils under different cropping systems in a changing climate for future projections of soil functions and associated ecosystem services
Optimize soil structure and avoid soil compaction	<ul style="list-style-type: none"> Assessment of the extent and severity of surface and subsoil compaction in Europe Impact of field traffic and livestock trampling on soil structure, soil functions and plant growth in different pedoclimatic zones Improved mechanistic understanding of the soil compaction process Evaluating the influence of soil compaction on GHG emissions Extent and impact of soil compaction on soil functions in a changing climate Assessing persistence and natural resilience of compacted soils, and assessing potential of region-specific nature-based solutions at local and landscape scales
Avoid soil erosion	<ul style="list-style-type: none"> Developing or improving monitoring programs for wind, water and tillage erosion and their impact on soil function losses Harmonization of erosion rates evaluation across Europe and standardization of national erosion measures and estimates Improving soil erosion modelling by including the role of biodiversity Assessing the impact of climate change on soil erosion
Avoid soil salinization	<ul style="list-style-type: none"> Increase understanding of salinization processes due to the implementation of cropping systems including irrigation across Europe Monitoring salinization Impact of climate change on the extent and consequences of salinization Understanding SOC dynamics in saline soils, to predict the effects of salinity on soil functions
Enhance nutrient retention and use	<ul style="list-style-type: none"> Increased insight into methods to reduce nutrient leaching and mineral fertilizer use Development of a holistic and multi-criteria approach for soil fertility assessment
Enhance soil biodiversity	<ul style="list-style-type: none"> Knowledge on the relationships between biodiversity and functions of soil organisms Standardization of biological indicators
Maintain/increase SOC	<ul style="list-style-type: none"> Definition of reference values for different soil types and functions. Consequences of SOM decline on soil functions Standardized, international, easy-to-use method for SOC stock assessment Soil organic carbon monitoring at national and international scales Improved SOC modelling Impact of deep roots on SOC stocks Role of soil biodiversity in maintaining and restoring SOC Processes affecting SOC in different soil fractions C sequestration potential in soils associated with different management options in various pedoclimatic contexts Development and testing of innovative practices to avoid SOC loss and increase SOC stocks Scenario analyses for SOC in agricultural soils and related tools
Avoid peat degradation	<ul style="list-style-type: none"> Accurate estimation and monitoring of peatland Consequences of peatland rewetting on SOC and other GHG emissions

(Continues)

TABLE 1 (Continued)

Avoid N ₂ O/CH ₄ emissions	Life cycle analysis of contrasting agricultural systems to evaluate their overall performances in terms of SOC sequestration and GHG emission
	Trade-offs between SOC sequestration and GHG emissions
	Consequences of rewetting peatlands on GHG emissions

Abbreviations: GHG, greenhouse gas; SOC, soil organic carbon; SOM, soil organic matter.

because of the many associated benefits and because of the low cost compared to other carbon removals solutions (Amelung et al., 2020; Bossio et al., 2020). Regarding the Green Deal targets, it can be noted that increasing C removals by 20% by 2030 would, if the effort was applied only to soils, represent an annual increase of +2.5% of current SOC stocks, which is clearly unrealistic (Bamière et al., 2023; Jordon et al., 2022; Wiesmeier et al., 2020). Reducing losses of C from C-rich soils such as peat soils is also necessary and deserves more attention, as European peatland represent only 2% of arable land, but 25% of its GHG emissions (ECA, 2021).

3.2.1 | Understanding the natural system to optimize ecosystem services, soil health and (bio)diverse landscapes

While much research has addressed soil organic matter (SOM) dynamics in the last decades, protecting and increasing SOC stocks still requires a better understanding of the processes governing their accrual and persistence. The specific role of soil biodiversity, the contribution of root systems and rhizo-deposits, and the influence of processing the biomass (e.g., through composting or pyrolysis) on SOC stocks and their persistence are key knowledge gaps emerging from the consultation (Table 1). The consultation was in agreement with the literature reviewed (Amelung et al., 2020; Chenu et al., 2019; Dignac et al., 2017; Wiesmeier et al., 2019). To ensure that agricultural soils' management protects or increases SOC stocks without increasing non-CO₂ GHG emissions, the trade-offs between SOC storage and N losses must be understood and predicted, to be able to propose effective mitigation options. Improved biogeochemical models and their coupling with climate and socio-economic models appear necessary to run scenario analysis for SOC stocks and GHG emissions from agricultural soils (Table 1) (Barbieri et al., 2021; Hauck et al., 2019). In particular, the question arises of the consequences of implementing management changes to comply with Farm to Fork targets (e.g., reducing fertilizer inputs by 20%) on soil

carbon and nitrogen stocks and fluxes, which has been little addressed so far.

3.2.2 | Agro-ecological solutions for climate-smart sustainable soil management

The capacity of a range of agricultural practices to store additional carbon in soils and mitigate GHG emissions has been assessed and is used for national or international assessments (Bamière et al., 2023; Lugato et al., 2014; Pellerin et al., 2017; Smith et al., 2008). However, robust estimates of the technical, economic, and achievable potential to store C at the scale of landscapes, regions, or countries are lacking and the methodology needs to be standardized (Rodrigues, Fohrafellner, et al., 2021; Rodrigues, Hardy, et al., 2021) (Table 1). Innovative practices affecting the biological functioning of soils are yet to be developed. The stakeholder consultation pointed out at the need to consider agricultural systems in their complexity (e.g., agroforestry, organic agriculture, conservation agriculture) rather than considering only individual agricultural practices (e.g., no tillage, crop residue return) (Table 2).

3.2.3 | Social and economic sustainability; enabling conditions

Recent analyses and the stakeholder's consultation in the framework of the EJP SOIL (Munkholm & Zechmeister-Boltenstern, 2021; Thorsøe et al., 2021) showed that the enabling conditions for the implementation of climate-smart agricultural soils management options are not yet in place. The need for analysis of the strengths and weaknesses of result-based payment approaches for SOC sequestration and GHG mitigation and proposals for appropriate payment schemes was identified. Payment schemes will require that Measuring, Reporting and Verification (MRV) systems and schemes are in place. 'Standardized, international, easy-to-use methods for SOC stocks assessment' and 'insufficient monitoring and the need for common monitoring systems on national and international bases' were identified among the top knowledge gaps regarding

TABLE 2 Knowledge gaps identified, during the European Joint Programme (EJP) SOIL stakeholder consultation, regarding soil management options and their influence on the EJP SOIL goals.

	Knowledge gaps	Climate change mitigation	Preserving and restoring ecosystems and biodiversity	Farm to Fork Strategy
Crops/crop rotations	(i) Effects of region and soil-specific crop diversification, including diversification at cultivar and genetic level, on spatial and temporal dynamics of SOC and nutrients, on soil biodiversity and soil functions	x	x	x
	(ii) Potential of perennialization and optimization to provide multiple ecosystem services (e.g., limit trade-offs of soil C sequestration on N ₂ O emissions)	x	x	x
	(iii) Impact of cropping history and crop rotations (including cover and catch crop) on soil quality (biological, physical, chemical properties and functions), with a focus on the effects of crop diversification on soil biodiversity and related soil functions		x	x
	(iv) Effect of below-ground inputs on soil C sequestration	x	x	x
Organic matter and nutrients management	(i) Impact of grassland management on SOC storage and nutrient cycling, and soil biodiversity conservation	x	x	x
	(ii) Effects of organic amendments (manure, residues, biochar, etc.) on soil processes yielding multiple ecosystem services, i.e., soil C storage, GHG emissions, crop yield, nutrient losses, water availability, erosion control, soil biodiversity conservation	x	x	x
	(iii) Region specific assessment of the effect of organic resources on SOC storage and soil quality, including soil fertility	x	x	x
	(iv) 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	x		
	(v) Effect of processing organic resources on soil C sequestration, GHG emissions and soil health	x	x	x
	(vi) Development of decision support tools for optimizing the use of organic resources	x		x
	(vii) Impact of circular use of biomass on the environment	x	x	
	(viii) Development of fertilization schemes		x	x
	(ix) Potential of organic wastes for SOC storage and the processes for how to make them safe for use in agriculture	x	x	x
	(x) Biochar and its potentials	x	x	x
Tillage and traffic	(i) Assess the effects of reduced tillage and no-tillage on soil biological, chemical, physical properties, processes and ecosystem services	x	x	x

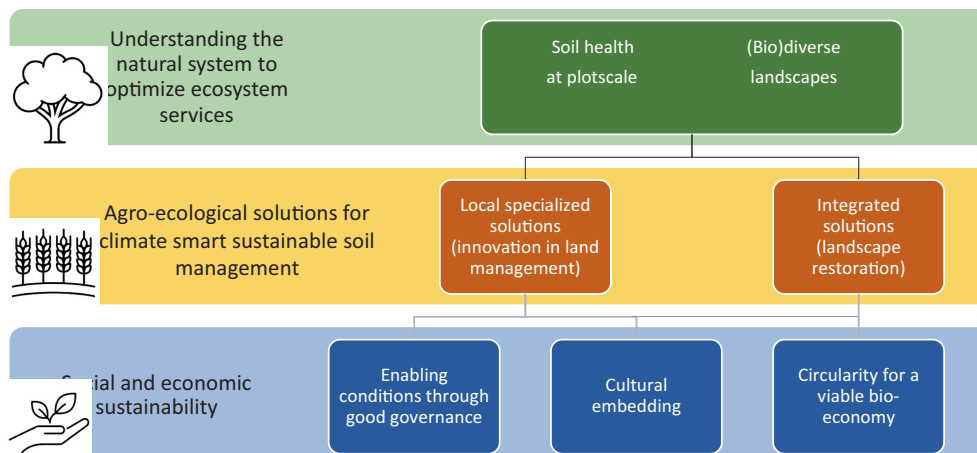
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TABLE 2 (Continued)

	Knowledge gaps	Climate change mitigation	Preserving and restoring ecosystems and biodiversity	Farm to Fork Strategy
	(ii) Improve region-specific knowledge on conservation tillage to mitigate soil erosion and weed control in relation to management		x	x
	(iii) Assess management practices to mitigate sub-soil compaction		x	x
	(iv) Develop engineering solutions to limit risk of compaction (e.g., lightweight robots, intelligent traffic and associated farm management)			x
	(iv) Further mechanistic and quantitative understanding of tillage effects on soil C storage, N ₂ O emissions, soil biodiversity (abundance, functional and specific diversity) and the interaction of several factors including soil type, C and nitrogen (N) status, and climate, to ultimately support land management, ES assessment, and policy development	x	x	x
Soil water management	(i) Site specific studies on efficient water management in a changing climate		x	x
	(ii) Developing holistic concepts for system/modelling studies on management strategies including irrigation		x	x
	(iii) Analysing factors affecting water holding and filtering capacity for different soils/farming system systems		x	x
	(iv) Insights into drought resistant crops, growth stage-water restriction relationship for different crops and soils			x
	(v) Knowledge on improved water management (sub-surface drainage and tillage) in peatlands	x		x
Agroforestry	(i) Potential of agroforestry as a soil improving cropping system in Europe	x	x	x
	(ii) Evaluation of trade-offs and synergies of ecosystem services provided by agroforestry systems at different spatial scale	x	x	x
	(iii) Potential of intercropping and/or pastoralism with tree-crops	x	x	x
Cropping systems	Assessing the effect of cropping systems in their complexity on soil C sequestration and soil ecosystem services	x	x	x
Soil restoration	(i) Potential of regenerative agriculture	x	x	x
	(ii) Role of biodiversity in soil restoration and (long-term) effects of chemical farming (using fertilizers and agro-chemicals) on soil functions	x	x	x
	(iii) Alternative weed control measures		x	x
	(iv) Management options for soil fertility restoration			x
	(v) Agricultural potential for peri-urban areas to avoid and restore sealed soils		x	x

Abbreviations: ES, ecosystem services; GHG, greenhouse gas; SOC, soil organic carbon.

FIGURE 3 Three layers for sustainable soil management: the biosphere: healthy soils and (bio)diverse landscapes (green bar); solutions: based on functioning of the natural system (yellow bar); enabling conditions: finding the social and economic enable conditions (blue bar).



SOC sequestration (Table 1). High throughput methods based on proximal and remote sensing must be developed in that perspective (Barbetti, 2021; Vaudour et al., 2022) as well as robust models and the use of accurate soil information (Smith et al., 2020).

3.3 | Green Deal goal ‘Preserving and restoring ecosystems and biodiversity’

The Green Deal goals described in the biodiversity strategy have been formalized in the new Nature Restoration Law, proposed by the European Commission in June 2022, such as restoring at least 20% of land surface area by 2030 (EC, 2022a, 2022b).

3.3.1 | Understanding the natural system: Soil processes leading to healthy soils with a diversity of soil functions and (bio)diverse landscapes

Traditionally, the soil processes are described in three categories: physical processes, chemical processes and biological processes. During the assessment of knowledge gaps in the EJP SOIL, topics were identified that are based on these process categories. Currently, land degradation is continuing at an accelerated rate. To curb this trend and avoid further degradation, the three main physical processes mentioned were related to ‘enhancing water storage, avoiding soil erosion and optimizing soil structure’. For the chemical processes, the main topics were ‘enhancing nutrient retention’ and ‘avoid soil salinization’ (Hassani et al., 2021). For soil biological processes, the topic of ‘Maintain/increase SOC for soil biodiversity’ was raised. For each of these topics a range of research gaps were identified (Table 1). We can highlight here that these topics are inter-related. As an example: enhancing SOM and soil biology

will improve the infiltration capacity and soil water storage capacity (Chenu et al., 2000; Di Prima et al., 2018; Liu et al., 2019) as well as make the soils more resilient to soil erosion (Cerdà et al., 2020; Morvan et al., 2018) and soil compaction (Busse et al., 2021; Schjønnning, 2023). Research that integrates process knowledge from different specialist areas is hence needed. Such as processes need to be studied over different temporal and spatial scales. Especially in climatic zones with erratic weather conditions such as the Mediterranean, it is important to measure and monitor soil and water processes over a long period of time, preferably in long-term experimental sites.

3.3.2 | Agro-ecological solutions for climate-smart and sustainable soil management: Local adapted and holistic solutions with their enabling conditions

The stakeholder consultation indicated a range of soil management solutions that could potentially be beneficial for sustainability of the agro-ecosystem and for the natural environment around agricultural areas. However, the stakeholders indicated that there are still many uncertainties and knowledge gaps when it comes to their exact impacts and where and when each of these management options would give the best return. Regarding crops/crop rotations, the need for region- and soil-specific crop diversification is the most urgent (Table 2) as also outlined by Zhang et al. (2020). However, as was indicated by Beillouin et al. (2019), precise information for specific soils is still lacking. For the use and management of organic matter and nutrients, we need to assess the impact of circular use of biomass and its effect on the environment (Muscat et al., 2021). Another highlighted knowledge need relates to ambition to have reduced tillage and traffic and more organic farming. In many cases, no-till leads to reliance on the use of herbicides for weed

control, hampering the ambition to reduce pesticide use, and potentially destroying soil life (Cerdà et al., 2020; Keesstra et al., 2019). Therefore, knowledge on the total impact and trade-offs of tillage/no-tillage systems on soil biology is urgent.

The next topic that was raised was how soil salinization will worsen due to climate change. It will affect areas where it is currently not yet a problem (Clarke et al., 2018) and it is needed to find solutions to mitigate the build-up of salts by different water management strategies and using different cropping systems. The last two topics are related to soil and landscape restoration options (Table 2). Agroforestry is one option that needs to be explored in more detail. Solutions like food forests and options like agro-pastoralism may make agro-ecosystems sustainable and climate resilient. Also high density grazing and other systems that mimic a more natural system (Franke & Kotzé, 2022) need to be explored to assess their sustainability for the biosphere as well as socio-economically. These types of solutions based on natural processes (nature-based solutions [NBS]; Keesstra, Nunes, Novara, et al., 2018) are key to finding solutions for soil and landscape restoration (Laforteza et al., 2018; van Rooij et al., 2021) that still allow landowners, and specifically farmers, to make a good living while maintaining and restoring the land and soil system to provide maximum ecosystem services.

Five specific topics of knowledge gaps regarding the development of solutions were identified by the EJP SOIL community and stakeholders from the participating countries: (i) Develop soil monitoring programs and modelling studies to support sustainable management decisions at a site-specific level under different climate-change scenarios; (ii) Develop site-specific, precision agro-ecological practices to improve soil ecosystems; (iii) Evaluate farm-level drainage systems to minimize environmental impacts; (iv) Study 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 their potentials for sustainable agricultural systems; and (vi) Develop analytic approaches (laboratory or experimental fields) and farm scale to assess differences from controlled and real-life conditions.

3.3.3 | Social and economic sustainability; enabling conditions, social acceptance, circular bio-economy

The enabling conditions needed include a variety of elements listed in Table 2. The targets cannot be met if the social and economic sustainability is not adequately addressed.

Good governance and social acceptance for the goal 'Preserving and restoring ecosystems and biodiversity' needs to pay attention to understanding the adoption barriers and opportunities for organic farming, but also, in the design of effective policies and how to successfully implement them. Only then can the circular economy be developed by sustainably using the natural resources: closing nutrient, energy and biomass circles.

3.4 | Green Deal objective Farm to Fork

The Farm to Fork Strategy's main objective is to support a fair, healthy and environmentally friendly food system in the EU. A set of objectives related to soil are defined in the strategy: (i) ensuring food security, (ii) improving plant health in a climate-change context and (iii) facilitating a shift to more healthy and sustainable human diets.

3.4.1 | Understanding the natural system to optimize ecosystem services; soil health and (bio)diverse landscapes

Improved understanding of the natural system is important for meeting all the specific targets of the Farm to Fork Strategy. Clearly, the identified need for improved insight into mechanisms and processes for increased nutrient retention and use (Table 1) is critical for meeting the targets of 50% reduced nutrient loss and 20% reduced fertilizer use. Improved monitoring and modelling of soil erosion—and thus of the loss of nutrients by erosion—will provide enhanced knowledge foundation for developing solutions to meet the reduced nutrient loss target. A number of knowledge needs emerging from the consultation and literature analysis refer to the effects of climate change and soil threats (e.g., compaction, salinization, erosion) on soil processes. These pressures must be accounted for when assessing the feasibility of reaching the Farm to Fork quantitative targets and scenario modelling appears as a key tool. The knowledge gaps listed in Table 1 are all essential for developing solutions to meet the targets on 25% of EU agricultural land under organic farming and ensuring food security. For the development of effective strategies, the solutions need to be tested in long-term experimental sites.

3.4.2 | Agro-ecological solutions for climate-smart sustainable soil management

There has been no explicit focus on management options to reduce pesticide use within EJP SOIL, as the efforts are

concentrated on other soil challenges, in particular climate mitigation and adaptation. Knowledge gaps are, however, identified on alternative weed control measures (Table 2)—particularly within an organic farming context. Moreover, a range of other knowledge gaps of clear relevance for plant protection (i.e., weed, pest and disease control), and thus pesticide use, are identified. The gaps reported for crop diversification, perennialization and cover cropping (Table 2) are also of vital importance for plant protection. Thus, synergies in relation to reduced pesticide use are expected. Crop diversification and cover cropping are known as effective plant protection strategies in arable farming (Gerhards & Schappert, 2020; Hofmeijer et al., 2021; Sharma et al., 2021). Inclusion of perennials may also contribute to weed control as shown by, for example, Melander and McCollough (2020). Also reduced and no-tillage effects are crucial relative to plant protection. Reduced and no-tillage are expected to yield benefits on a range of soil functions and services but may also result in trade-offs in terms of increases problems with weeds, pests and diseases and thus pesticide use (Nichols et al., 2015), especially in monoculture cropping systems (Nichols et al., 2015). Given the fact that there is a strong reliance on glyphosate for weed control in reduced and especially no-tillage systems (Fogliatto et al., 2020), research in optimizing reduced and no-tillage systems is needed to reach a 50% reduction in pesticide use.

In relation to the target on 50% reduction in nutrient losses and 20% reduction in fertilizer use, the EJP SOIL EU-wide stocktake (Higgins et al., 2021, 2023) found that there is a wide diversity in fertilization guidelines across Europe and a need for increased sharing of knowledge in terms of fertilization guidelines and analytical methods. Compared to mineral fertilization, the impacts of organic fertilizers on nutrients provision and SOM is much less known and needs to be investigated, accounting for the diversity of these amendments (manures, composts, digestates, etc.) (Table 2). How diversified cropping and perennialization contribute to these targets and will be affected by ad-hoc management options also remains to be studied (Table 2). Crop rotations and extensive use of cover crops are well-known management tools to reduce risk of nutrient losses by leaching and runoff (de Notaris et al., 2018; Hansen et al., 2015; Lapierre et al., 2022). The identified knowledge gaps on conservation tillage and low impact field traffic focus directly on erosion control and thus mitigation of surface transport of nutrients. Further mechanistic understanding of tillage effects on C and N dynamics is also stressed, as knowledge need. Numerous studies have shown that nutrient loss (phosphorus (P) in particular) via erosion and surface runoff and leaching is strongly affected by tillage and traffic (Maharajan et al., 2021; Ulén

et al., 2010). Therefore, it is important to link these fields of research to find the solutions needed to reach the Green Deal targets; and as it shows in our inventory, many of the topics would need to be jointly researched (Table 2), calling for research that is interdisciplinary and jointly programmed by two or more Missions.

The target of 25% organic farming also increases emphasis on soil health. Organic farming is seen by many as a tool to sustain soil health through improved nutrient cycling, crop diversification, increased use of organic fertilizers and amendments, etc. (Tahat et al., 2020). Much less attention has been paid, however, to the need for healthy soils to reap the full benefits of organic farming. It is much more difficult to obtain success with organic farming if the soil is severely degraded at the beginning. In a study by Novara et al. (2019) in Spain, it was shown that the SOM content in the topsoil only started to recover 5 years after converting to organic farming. This may be caused by the lack of biodiversity in the soil at the start of the process of converting the available organic material (manure, litter) into SOM.

3.4.3 | Social and economic sustainability; enabling conditions

The knowledge gaps in relation to enabling conditions mentioned above for ‘Preserving and restoring ecosystems and biodiversity’ are also relevant in the context of meeting the targets of the Green Deal Farm to Fork Strategy.

Linking production and consumption dynamics in a value chain perspective is important for leveraging the food system to deliver soil ecosystem services such as food security, improving plant health in a climate-change context and facilitating a shift to more healthy and sustainable human diets. For instance, the composition of diets directly influence consumer demand and thus also which products farmers are requested to deliver; further, the design of delivery contracts influence farmers' ability to plan the timing of their fieldwork, taking local soil conditions into account (Perignon et al., 2017; Thorsøe et al., 2019). Specific attention should be given to the use of organic wastes in agriculture, in particular on how the circular bio-economy can be economically viable without compromising food quality. Therefore, lacking soil knowledge has been emphasized as an important shortcoming (Thorsøe et al., 2021). Increasing public awareness and societal engagement at all levels of the value chain, including with consumers, farmers, processors and policymakers, as the decisions of all these actors have a significant impact on the state of soils and the wider environmental impact of food production. To improve soil

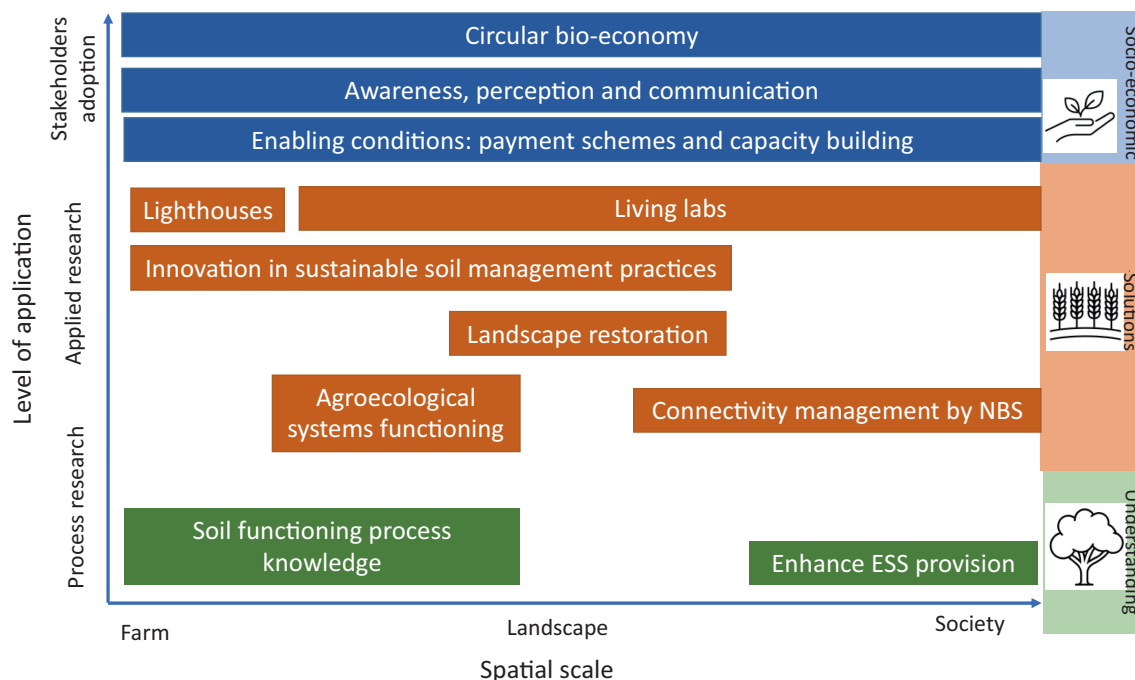


FIGURE 4 Merging the objectives: diagram to depict the need of an integrated approach. The identified knowledge gaps have been placed in relation to both the level of application and the spatial scale. ESS, ecosystem services; NBS, nature based solutions.

literacy, all stakeholders must have access to both general education on soil and targeted training for specialist needs, complementing formal education with demonstration activities, for instance, in Living Labs and via the EU Soil Observatory (European Commission, 2021a).

4 | DISCUSSION: KEY RESEARCH FOCI AND APPROACHES FOR REALIZING THE LAND AND SOIL RELATED GREEN DEAL TARGETS

The Mission Board Soil Health and Food gives suggestions on methodologies that support the line of thought described in Section 3 following the three-step approach: understanding the natural processes, finding management options which are solutions, and the enabling conditions. 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. Principles of the Mission include: (i) focus on communities; (ii) use a systems' approach (interfaces with land, water, atmosphere; soil as an element in ecosystems and landscapes; multiple demands; rural-urban relations); (iii) show that soils deliver essential ecosystem services for various sectors; (iv) account that soils are diverse and need locally adapted management; and (v) monitor soils continuously (Veerman et al., 2020).

From the inventory and analysis done during the soil stakeholder consultation in EJP SOIL, it has become clear that there is a need for different types of research. As shown in the previous sections we can organize the needed research for sustainable development over two main axes: (i) scale, from soil health at plot scale to the (bio)diverse landscape or society scale; and (ii) type of research, from process-based research to target oriented and to applied research (Figure 4). The more fundamental research topics focus on a specific spatial scale, while the applied research topics do not have a spatial scale for which they are specifically relevant.

4.1 | Understanding the natural system to optimize ecosystem services, soil health and (bio)diverse landscapes: Process-oriented research (green boxes in Figure 4)

4.1.1 | Soil functioning process knowledge: How does it work?

The functioning of the natural system needs to be understood to be able to manage it sustainably. Interactions between soil processes (physical, chemical, biological) and their impacts on hydrological, sedimentological, biogeochemical, and agronomical processes need to be known, as well as knowing how local processes impact

the landscape scale, or how the landscape impacts the processes at point, field or farm level to enhance ecosystem services provision at local and landscape scales. Much research so far focusses on a single scale (plot, farm, landscape or even larger, such as European or even global scale, Borrelli et al., 2021, for erosion), and does not consider nested spatial scales. Linking between the different scales, from plot to farm to landscape scale, is a key research gap while this is essential for ensuring scaling up of sustainable measures in agriculture (Keesstra, Nunes, Saco, et al., 2018; Stolte et al., 2016).

There is also a need for simple, easy to use methodologies to assess soil functions and thereby soil quality and soil health. In addition, research is needed to determine realistic and achievable soil health conditions for a specific location. For instance, to access the potential of a specific location for soil carbon sequestration, in terms of the achievable SOC sequestration potential (Chenu et al., 2019; Lessmann et al., 2022; Smith, 2004).

4.1.2 | Enhancing ecosystem services provision through soil health

In our knowledge gap analysis, the effect of complex interactions between cropping systems and soil ecosystems was mentioned repeatedly. As was shown by Keesstra, Pereira, et al. (2016) and Keesstra, Bouma, et al. (2016), there is a strong link between soil functions and ecosystem services (and the SDGs also). In another paper by Smith et al. (2021), the soil is shown to be essential for most of 'Natures contributions to people (NCP)', which highlight the great potential of soils to contribute to sustainable development. The paper and associated Special Issue recognize that poorly managed, degraded or contaminated soils cannot provide the necessary ecosystem services to reach the goals of both NCP and SDGs. Therefore, research on soil ecosystem services should address: (i) ways to protect healthy soils from land use change and degradation; (ii) soil management that enhances soil biodiversity and soil health; and (iii) ways to restore soil health in degraded soils. Keesstra, Nunes, Saco, et al. (2018) further developed this link to show that soil functions are the basis underpinning the transition towards sustainability. It was shown that solutions should be sought for using concepts such as regenerative economics, systems thinking, connectivity of sediment and water and nature-based solutions. In the design of sustainable management options, it is essential to assess trade-offs and synergies of ecosystem services provided by agroforestry systems at different spatial scales.

4.2 | Agroecological solutions for climate-smart and sustainable soil management: Applied research (brown boxes in Figure 4)

Gaining a solid understanding of the natural system allows for the design of solutions. The agroecological solutions that are needed to realize the Green Deal targets related to soil and landscapes can be so-called Nature Based Solutions. Again, it is important to take into account a wide range of scales: the full scope of physical scales—from plot to landscape—but also the human scale, in order to find solutions that are good for nature but also ensure socially acceptable and economically viable solutions. In this section, we look into the biophysical research needed for this.

4.2.1 | Agroecological functioning

Nature-based solutions are often associated with large-scale interventions in coastal and river management. However, such solutions are very relevant to agriculture as well. Different types of nature-based solutions can be identified: from the use of existing ecosystems (such as the soil biota delivering better nutrient provision to crops in organic farming) to constructed ecosystems (such as phytobiofilters for small scale wastewater treatment, Keesstra, Nunes, Novara, et al., 2018). There are many unknowns on the impact of the historical setting of a region, as the impact of the legacy from previous soil management cropping on soil quality (biological, physical, chemical properties and functions). To develop suitable nature-based solutions in each region, it is important to evaluate the selection of plant species, crops and soil management practices to best conserve the soil and water resources (Mancuso et al., 2021; Miralles-Wilhelm, 2021; Sonneveld et al., 2018). The self-reinforcing effect of the improvement of soil functions in relation to soil health and ecosystem services is an understudied topic that needs conceptual understanding, measurement and monitoring as well as modelling studies. This is needed to evaluate how the chosen soil/crop management impacts across spatial and temporal scales and soil ecosystem functioning. This systems understanding allows a more efficient and site-specific design of water and nutrient management.

4.2.2 | Connectivity management by Nature Based Solutions (NBS)

Starting from the landscape, the connectivity of water, sediment, solutes and solids, with associated substances

attached, is key in understanding how soil degradation impacts ecosystem services (Arnáez et al., 2015; Saco et al., 2020). Connectivity in the context of water and sediment have been studied in many landscape systems, in riverine systems (Fryirs et al., 2007), ecology (Fuller & Death, 2018), wildfire affected areas (López-Vicente et al., 2021) and agricultural areas (Rodrigo-Comino et al., 2020). These insights show that to understand how water and sediment transfers through landscapes, it is needed to understand the processes at the plot scale where soil properties are the fundament of the processes that occur. Runoff generation is determined by soil properties, but also by the surface properties and how the plant/litter cover is managed (Cerdà et al., 2021, 2022). Also, the structure and composition of the landscape, such as fragmentation, relief, diversity, etc., determines soil-water interactions substantially (Levavasseur et al., 2012, 2015). Agricultural practices, such as ploughing, litter management, terraced field and harvesting techniques, also impact the connectivity of the surface runoff and associated sediment transport and storage (Llena et al., 2019). The more complex landscape structures affect hydrological and geochemical processes and carbon sequestration potential (Kalantari et al., 2019). Even though the conceptual understanding of connectivity is quite well established, a remaining challenge is how to quantify connectivity (Keesstra, Nunes, Saco, et al., 2018) to be able to evaluate the effects of NBS on water and sediment fluxes.

Landscape restoration including agroecological soil management

In landscape restoration, several research gaps have to be filled, while implementing solutions simultaneously. Climate-smart sustainable agricultural practices need to be assessed on their potential for larger scale restoration as well as their potential to be a source of livelihood for farmers. Agroecology needs to find suitable weed control measures, solve fertilization issues, and use soil biodiversity and other nature-based solutions as alternatives to agro-chemicals (Fenster et al., 2021). A higher organic matter content in the soil can increase soil's water holding capacity that will reduce the need for irrigation (Taylor et al., 2021). These plot scale solutions need to be embedded in the landscape approach. The use of landscape elements can be a suitable option, as was demonstrated in China with different terrace systems (Feng et al., 2019) and with flowered strips to create a habitat for predators of the pests that attack the crops (Juventia et al., 2021). In addition to hedgerows, flowered strips can play an essential role in creating a (bio)diverse and healthy landscape. Some examples to be highlighted are agroforestry that is a soil improving cropping

system, as well as intercropping and pastoralism with tree crops (Pulido et al., 2001; Rolo et al., 2020). Landscape restoration needs to go hand in hand with smaller spatial scale restoration. Such restored landscapes are also more resilient to climate change, making landscape restoration a climate-adaptation strategy (Gusli et al., 2020). Although many papers have addressed agroecological soil management, there are still many knowledge gaps remaining. How and to what extent does crop choice (Cusworth et al., 2021), the implementation of agroforestry (Elevitch et al., 2018) and other types of mixed farming (Giller et al., 2021) make the natural system more resilient in the face of external pressures? But the key to success lies in merging farming and natural resource conservation (LaCanne & Lundgren, 2018), where soils form the basis of the system (Schreefel et al., 2020). This calls once more for interdisciplinary research, calling for systemic approaches that needs collaboration between hydrologists, agronomists, ecologist and soil scientists. Research is needed to combine systems knowledge with business models and culturally embedded solutions that use local/indigenous knowledge, restoring former management techniques that were sustainably used in the past (such as gravity driven flood irrigation).

Link landscape scale research to societal research: Living labs and lighthouses

To ensure the adoption of new sustainable agricultural practices, a link to the stakeholders implementing such measures is crucial. The proposed living lab approach in the Soil Mission can be very instrumental. In a living lab, the relevant stakeholders together develop their own regional specific ambitions, which need healthy soils as a basis of the whole system (biosphere, society, economy, governance). The living lab environment assures a joint learning approach, and research focussing on specific ecosystem services in which the contribution of soils to the regional aspirations become explicit. Important elements that need to be discussed and agreed upon in the living lab are the consequences of abandoning the management options that are evaluated as being unsustainable in that region (Visser et al., 2019). The living lab approach may be a way to stimulate this transition towards a circular bio-based climate-smart society and specifically targeting at agricultural sector, by social learning. The living lab can be used for joint experimenting and exploring together how to overcome barriers and exploit opportunities. The so-called local champions, leaders in the regions can play an important role. For this, approaches are needed to stimulate social learning (Bouwma et al., 2022), as well as an evaluation method that is generally accepted by the involved stakeholders.

4.3 | Social and economic sustainability: stakeholder's adoption (blue boxes in Figure 4)

The last step towards solutions for climate-smart sustainable soil management is the social and economic arena. Much research is needed to understand the perception and decision-making process of stakeholders. Socio-economic research is needed for finding the best solutions, both for nature as well as for humans. Three elements are highlighted here: enabling conditions, awareness raising, and the circular bio-economy.

4.3.1 | Enabling conditions: Payment schemes, capacity building, stakeholder adoption

There is a lack of clear economic benefits and uncertainties on profits linked with incoherent policies and incentives. The development of sound and targeted policies and incentives that also drive technological development (ICT based), is needed to improve the availability and adoption of sustainable and climate-smart practices without compromising farmers' profitability. There are many areas of improvement of soil research to respond adequately to the soil challenges and stakeholders' expectations, but this information needs to be brought more efficiently to the relevant stakeholders. There are also cultural, organizational, legal/institutional, economic, and political obstacles that do not allow proper exploitation of available knowledge (Mills et al., 2017). Therefore, there is a strong need for the creation of knowledge networks and national infrastructure linked to those operating at European level, and the development of regional tailored soil management strategies conducive to overcoming soil challenges.

In the first year, the EJP SOIL survey (Thorsøe et al., 2021), with respect to policy implementation, found that there is still a range of shortcomings. Also the ECA (European Court of Auditors) reported that in the two last CAP periods (2014–2020), the CO₂ emissions originating from the farming sector have not been curbed, despite expenditures beyond €100 million attributed to climate action (ECA, 2021). For example, (i) the rural development programme is still applied to improve drainage systems, although it is known to further degrade farmland (Thorsøe et al., 2022); (ii) the installation of drip irrigation on sloping land is still subsidized while this induces massive erosion problems (Hondebrink et al., 2017); and soil degradation (Puy et al., 2017) and (iii) the proposed eco-schemes under the

forthcoming CAP strategic plans will likely be insufficient to alter the course for European farmers (Hasler et al., 2022; Runge et al., 2022). Therefore, developing novel payment schemes facilitating behavioural change and perception of the farmers in a co-creative way is essential, as the uptake of sustainable practices is much more efficient if the farmers agree to the management change (Cerdà et al., 2019). Further, designing novel governance tools based on efficiency, effectiveness and legitimacy is needed for a successful transition towards sustainable soil management (Juerges & Hansjürgens, 2018). A transition from activity to result-based payments as proposed in the Green Deal may strengthen policy coherence, but as highlighted above, it should rest on solid a MRV system to ensure its credibility.

4.3.2 | Awareness raising, perception and communication

The lack of awareness on the links between soil health, food/product/water quality and safety and human health was flagged as a major issue in different reports (IPBES, IPCC, ECA, 2018, 2019).

How can we create a long-term vision: farmers as stewards of land and soil resources? For this, a shift is needed in the perception of the role of farmers within the general public, the majority of scientist and policy-makers. Moreover, (many) farmers need to change their perception on the potential of and need for climate-smart sustainable management of soils. In changing land-users' perceptions and facilitating learning between research and practice, bridging organizations like farm advisory services can play a crucial role. However, given the rapidly evolving agri-food sector and the focus on 'demand-driven advice', technical capacity building also needs to take place within the advisory service and is key for sustainable soil management (Ingram & Mills, 2019). Further, strengthening networks and peer-to-peer communication should be highlighted as effective platforms for knowledge exchange (Mills et al., 2017). Our vision, which was developed along the EJP SOIL, is to make soils a pivotal resource to enable the transition to a climate-smart, circular society, to which sustainable agricultural practices (soil and water management) contribute.

4.3.3 | Circular bio-economy

There are many aspects that are important to create the circular bio-economy: from household-level choices for food and energy (Keesstra et al., 2022), consumer

behaviour (Rana & Paul, 2017), to circular farming (Vrolijk et al., 2020). Building a circular economy can be seen as a holistic approach that brings sustainable resource management, which closes nutrient, energy and biomass circles. Knowledge is needed on how to find multi-purpose agro-ecological production systems that are economically viable, socially acceptable and long-term sustainable in the agricultural sector. Soil health is here an important criterion for assessing sustainability. There is a need for a modelling framework and a toolbox to evaluate how waste (or better side-streams) can be used to enhance the ecosystem functions without creating pollution problems. Potential trade-offs need to be evaluated. We also need stronger linkages between the agri-food and industrial sector in policies and regulations. Some questions that need to be answered are: How does the circular use of biomass impact the environment? How can we make sure that the use of organic wastes is safe in terms of human consumption? Apart from these technical questions, an array of social issues needs to be studied, ranging from behaviour of consumers to the business models of industries. It is important to try to find solutions that are recognized at regional level and provide solutions to fit needs and that are adapted to agricultural systems. However, sometimes, one would prefer radical changes (transitions) that may not fit local conditions at first site (Köhler et al., 2019).

5 | CONCLUSIONS

This paper gives an overview of how research on climate-smart sustainable management of soils can contribute to the objectives of the Green Deal, specifically those of the Climate Ambition, the Farm to Fork Strategy and the Biodiversity strategy. The analysis of the data collected during the EJP SOIL consultation and inventory (dating from before the launch of the Green Deal) evidenced the specific ways for research to efficiently contribute to the objectives of the European Green Deal:

- Research should:
 - be interdisciplinary (soil science, hydrology, agronomy, ecology, socio-economy) to look beyond the primary research question and assess and evaluate the synergies and trade-offs of selected management options for all ecosystem services and stakeholders involved.
 - include long-term experiments and infrastructures, to assess and evaluate the long-term impacts of selected management options;
 - not only focus on plot scale, but also on farm to landscape scales, to assess and evaluate the larger scale impacts of selected management options;
 - address the variability of effects and impacts on soil functions and related ecosystem services in different soil types, climates, geomorphological settings and agricultural systems;
 - co-construct solutions with end-users to design effective management options. This will ensure social acceptance and viable economic conditions.
- The socio-economic dimension should be taken into account when giving agricultural advice at farm level, including the interaction with society and the food chain in rural and urban areas (such as circular bio-economy). Hence, the socio-economic dimension is an essential element in soil research, insufficiently addressed so far.
- Successful agro-ecological solutions for climate-smart sustainable soil management will only be effective when social and economic sustainability is ensured. This can be done by considering the enabling conditions through good governance, social acceptance and viable economic conditions, that research should investigate.

AUTHOR CONTRIBUTIONS

S. D. Keesstra: Conceptualization; investigation; methodology; validation; visualization; writing – original draft; writing – review and editing; funding acquisition; formal analysis; project administration; supervision; resources. **C. Chenu:** Conceptualization; investigation; funding acquisition; writing – original draft; writing – review and editing; methodology; formal analysis; resources. **L. J. Munkholm:** Investigation; conceptualization; writing – original draft; funding acquisition; writing – review and editing; methodology; validation. **S. Cornu:** Conceptualization; investigation; writing – original draft; writing – review and editing; formal analysis; validation. **P. J. Kuikman:** Conceptualization; writing – original draft; funding acquisition; investigation; validation; writing – review and editing; methodology. **M. H. Thorsøe:** Writing – original draft; writing – review and editing; investigation; validation; methodology. **A. Besse-Lototskaya:** Writing – original draft; writing – review and editing; methodology; project administration. **S. M. Visser:** Conceptualization; investigation; funding acquisition; writing – original draft; methodology; validation; writing – review and editing; visualization; project administration; resources.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in EJP SOIL website at <https://ejpsoil.eu>.

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