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

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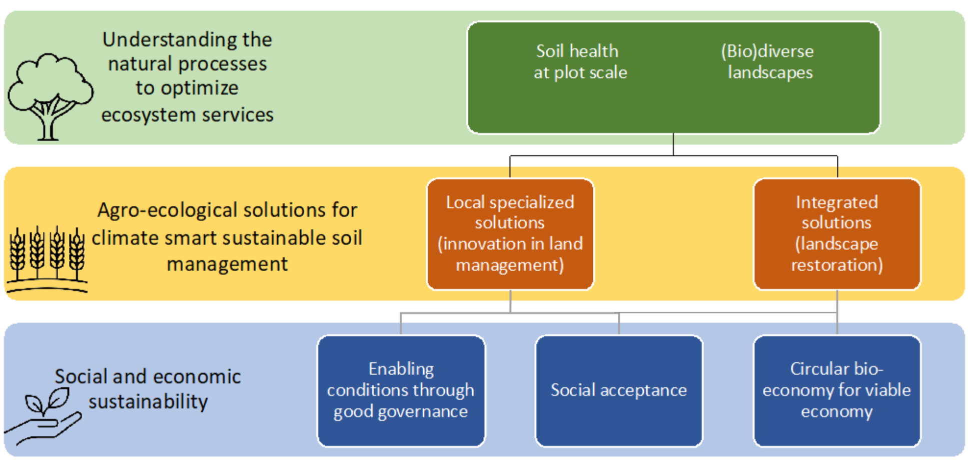
**Graphical abstract**





# 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, 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, specifically the Climate Ambition, the Farm to Fork Strategy and the target to preserve and restore eco-systems and biodiversity. 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 set by the European Commission. 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 (a) on plot scale when mobilizing soil processes and on landscape scale when addressing sediment and water connectivity and biodiversity management; and (b) address the enabling conditions through good governance, social acceptance and viable economic conditions.

**Keywords:** soil management knowledge, Sustainable Development Goals, (bio) diverse landscapes, soil health, soil information, science-policy interface

**Highlights**

1. **Research on climate-smart sustainable management of agricultural soilsis key to the soil related objectives of the Green Deal.**
2. **Soil research needs to be transformed to include: interdisciplinarity, long-term experiments, multi-scale, include trade-offs and multi-actor approaches.**
3. **More research should focus on enabling socio-economic for the adoption of the climate-smart sustainable soil management practices.**

# 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 challenge 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 (Panagos et al., 2018; Hossain et al., 2020). 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 restoring ecosystems, the intensification and industrialization of the agricultural sector is still ongoing, with ever larger scale mono-cropping and use of pesticides, heavy machinery and herbicides and excessive use of (synthetic and organic) fertilizers (Panagos et al., 2018; Hossain et al., 2020). 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 that 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 been amended setting a new objective for achieving climate neutrality in the entire land sector, earlier, by 2035 (European Commission, 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-$CO_2$ 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 pesticide by 50%; reduce nutrient losses by 50% and fertilizer use by 20%; reduce antimicrobials in farmed animals by 50% 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 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 and Panagos, 2021). First, soils will be impacted by measures implemented to respond to the Green Deal objectives, such as that of reducing greenhouse gas emissions in the LULUCF sector, which will require reducing GHG emissions from soils. Halting biodiversity loss will benefit to soil biodiversity and reducing the use of pesticide will reduce soil contamination. Second, a 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 EJP SOIL (www.ejpsoil.eu), with as 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. FAO defines climate-smart agriculture at 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 stakeholders 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 European Joint Programme 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", i.e. a group of stakeholders comprising representatives from main soil stakeholder groups including academics, policy makers, NGO's and farmer organisations or farmers, with the mission of providing input and feedback to the EJP SOIL programme and 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 ICT (Information and Communication Technology (Pavlů et al., 2021) tools; iii) Estimates of achievable soil carbon sequestration on agricultural land in the EU (Rodrigues 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 Ruysschaert et al. (2021); D2.6 by Munkholm et al. (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 program. This paper used the part of the collected data that was related to knowledge development.

## 2.2 The Green Deal as a guide

We did relate the knowledge needs that emerged from the stakeholder consultation to the objectives of three Green Deal strategies (Fig. 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.

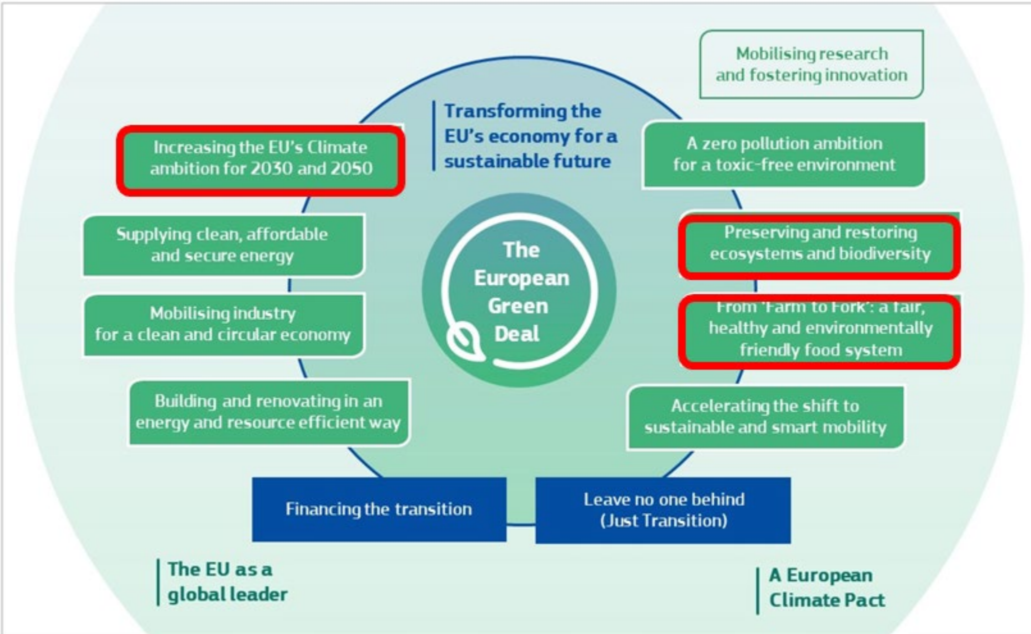



*Figure 1: The Green Deal objectives (European Commission, 2019. Red delineation indicates the objectives that strongly benefit from sustainable soil management).*

## 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: 1) soil health at the plot scale, 2) (bio)diverse landscapes and 3) 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 that soils provide ecosystem services on different temporal and spatial scales.
Soil health is most often assessed at the local scale, i.e. the plot scale. However, considering larger spatial scales are essential as soils are interconnected thought 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 (Fig. 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 (Fig. 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 (Fig. 2).

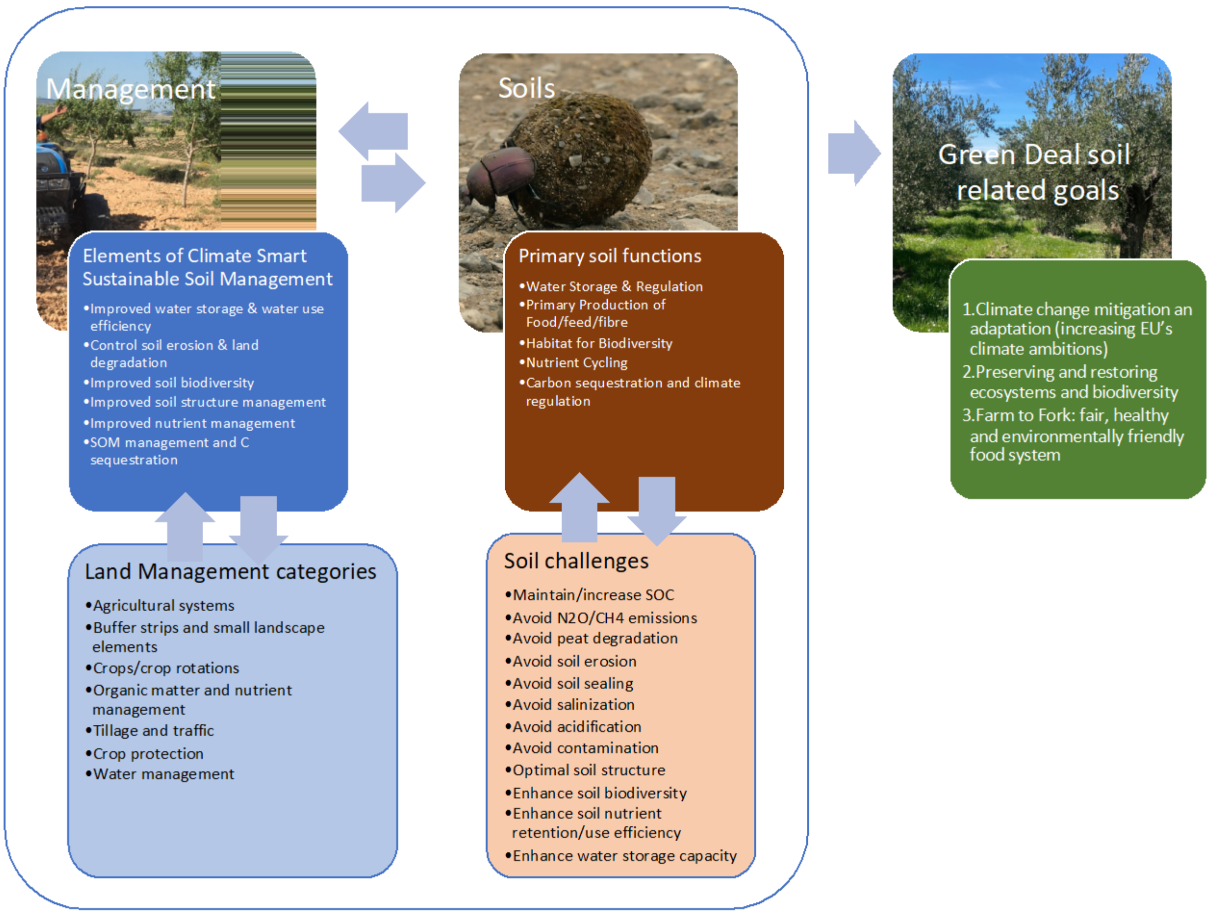



*Figure 2: Conceptual framework explaining the linkages between the soil functions and the current soil challenges; the land management categories and current climate smart sustainable soil management options. Implementing adequate soil management options will influence soil functions in a way that will enable the contribution of soils to the achievement of the soil related Green Deal goals.*

## 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 Fig.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 systems thinking when designing solutions is 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.

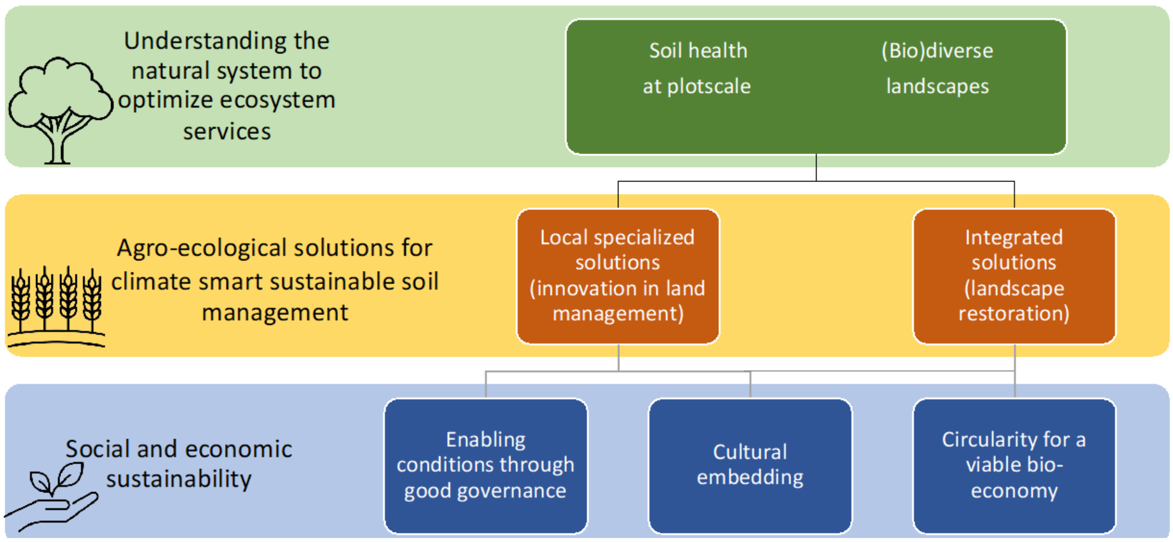



*Figure 3: Three layers for sustainable soil management: the biosphere: healthy soils and (bio)diverse landscapes (green bar); solutions: based on functioning of the natural system (yellow bar); enabling conditions: finding the social and economic enable conditions (blue bar).*

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 Fig. 3), we have identified research 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, i.e. 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 Land use, Land use-change and forestry (LUCUCF) sector is expected to achieve climate neutrality by 2035 (EU, 2018), which is estimated to correspond to a decrease of non-$CO_2$ 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 of non-$CO_2$ emissions ($N_2O$ and $CH_4$). Soils are estimated to be responsible of 36% of EU $N_2O$ emissions (ECA, 2021). Soils also representing 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 SOC storage potentials 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 because of the many associated benefits and because the low cost compared to other carbon removals solutions (Bossio et al. 2020; Amelung 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 asked only to soils, represent an annual increase of +2.5% of current SOC stocks, which is clearly unrealistic (e.g., Bamière et al. 2023; Wiesmeier et al. 2020; Jordon et al. 2022). 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).

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

While much research has been addressing soil organic matter dynamics in the last decades, protecting and increasing SOC stocks still requires to better understand 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 (e.g. Amelung et al. 2020, Dignac et al. 2017; Chenu et al., 2019; Wiesmeier et al. 2019). To ensure that agricultural soils management protects or increases SOC stocks without increasing non-$CO_2$ 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 socioeconomic models appear necessary to run scenario analysis for SOC stocks and GHG emissions from agricultural soils (Table 1) (Hauke et al. 2019; Barbieri-I et al. 2021). 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.

## 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 (Smith et al. 2008; Lugato et al. 2014; Pellerin et al. 2017; Bamière et al. 2023). 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 et al. 2021) (Table 1). Innovative practices affecting the biological functioning of soils are yet to be developed. The stakeholders 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).

## Social and economic sustainability; enabling conditions

Recent analyses and the stakeholder's consultation in the framework of the EJP SOIL (Thorsøe et al., 2021; Munkholm and Zechmeister-Boltenstern, 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 SOC sequestration (Table 1). High throughput methods based on proximal and remote sensing must be developed in that perspective (Nocita et al. 2015; 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, 2022).

### 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 in 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'. 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 interrelated. As an example: enhancing soil organic matter (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 (Morvan et al., 2018; Cerdà et al., 2020) and soil compaction (Schjønning, 2023; Busse et al., 2021). 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.

### 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 the 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 the 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 (Keesstra et al., 2019; Cerdà et al., 2020). 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 and Kotze, 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 et al., 2018a) are key to finding solutions for soil and landscape restoration (Lafortezza 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 eco-system 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 scenario's; 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.

## 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 the circular economy can be developed by sustainably using the natural resources: closing nutrient, energy and biomass circles.

*Table 1: Identified knowledge gaps related to soil processes in relation to soil challenges collected during the EJP SOIL*

| | |
|---|---|
| Enhance water storage | Assessment of water storage capacity at the root zone level<br>Influence of agroecological practices and systems on soil infiltration capacity<br>Influence of agroecological practices and systems on blue- and green water trade-offs<br>influence of agroecological practices and systems on water storage capacity for different soil types and SOC contents<br>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 | 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 | Developing or improving monitoring programs for wind, water and tillage erosion and their impact on soil function losses<br>Harmonization of erosion rates evaluation accross Europe and standardization of national erosion measures and estimates<br>Improving soil erosion modelling by including the role of biodiversity<br>Assessing the impact of climate change on soil erosion |
| Avoid soil salinization: | 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 retentiona and use | Increased insight into methods to reduce nutrient leaching and mineral fertilizer use<br>Development of a holistic and multi-criteria approach for soil fertility assessment. |
| Enhance soil biodiversity | Knowledge on the relationships between biodiversity and functions of soil organisms |
| | Standardization of biological indicators |
| Maintain/increase SOC | Definition of soil organic matter reference values for different soil types and functions. Consequences of SOM decline on soil functions<br>Standardised, international, easy-to-use method for SOC stock assessment<br>Soil organic carbon monitoring at national and international scales<br>Improved SOC modelling<br>Impact of deep roots on SOC stocks<br>Role of soil biodiversity in maintaining and restoring SOC<br>Processes affecting SOC in different soil fractions<br>C sequestration potential in soils associated with different management options in various pedoclimatic contexts<br>Development and testing of innovative practices to avoid SOC loss and increase SOC stocks<br>Scenario analyses for SOC in agricultural soils and related tools |
| Avoid peat degradation | Accurate estimation and monitoring of peatland |
| | Consequences of peatland rewetting on SOC and other GHG emissions |
| Avoid N2O/CH4 emissions | Life cycle analysis of contrasting agricultural systems to evaluate their overall performances in terms of SOC sequestration and GHG emission<br>Tradeoffs between SOC sequestration and GHG emissions<br>Consequences of rewetting peatlands on GHG emissions |

***Table 2: Knowledge gaps identified, during the 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 $N_2O$ 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, viz. 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*** |
| | ***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.*** | ***x*** | | |
| | ***iv) Effect of processing organic ressources on soil C sequestration, GHG emisions and soil health*** | ***x*** | ***x*** | ***x*** |
| | ***v) Development of decision support tools for optimizing the use of organic resources*** | ***x*** | | ***x*** |
| | ***vi) Impact of circular use of biomass on the environment*** | ***x*** | ***x*** | |
| | ***vii) Development of fertilization schemes*** | | ***x*** | ***x*** |
| | ***viii) Potential of organic wastes for SOC storage and the processes for how to make them safe for use in agriculture*** | ***x*** | ***x*** | ***x*** |
| | ***ix) 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* |
| | *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, $N_2O$ emissions, soil biodiversity (abundance, functional and specific diversity) and the interaction of several factors including soil type, C and N status, and climate, to 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 in 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-off's 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) effect 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* |

## 3.3Green 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.

### 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.

### 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, perenialization 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 (Hofmeijer et al., 2021 Sharma et al., 2021; Gerhards and Schappert, 2020). Inclusion of perennials may also contribute to weed control as shown by, e.g., Melander et al. (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 tradeoffs 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 soil organic matter is much less known and needs to be investigated, accounting for the diversity of these amendments (manures, composts, digestates…)(Table 2). How will diversified cropping and perennialization contribute to these targets and 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 (Lapierre et al., 2022; de Notaris et al., 2018; Hansen et al., 2015). 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 (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 field 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 research (Table2), 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.

### 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 the 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 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, 20121a).

## 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 on plot scale to the (bio)diverse landscape or society scale; and ii) type of research, from process research to target oriented and to applied research (Fig. 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.

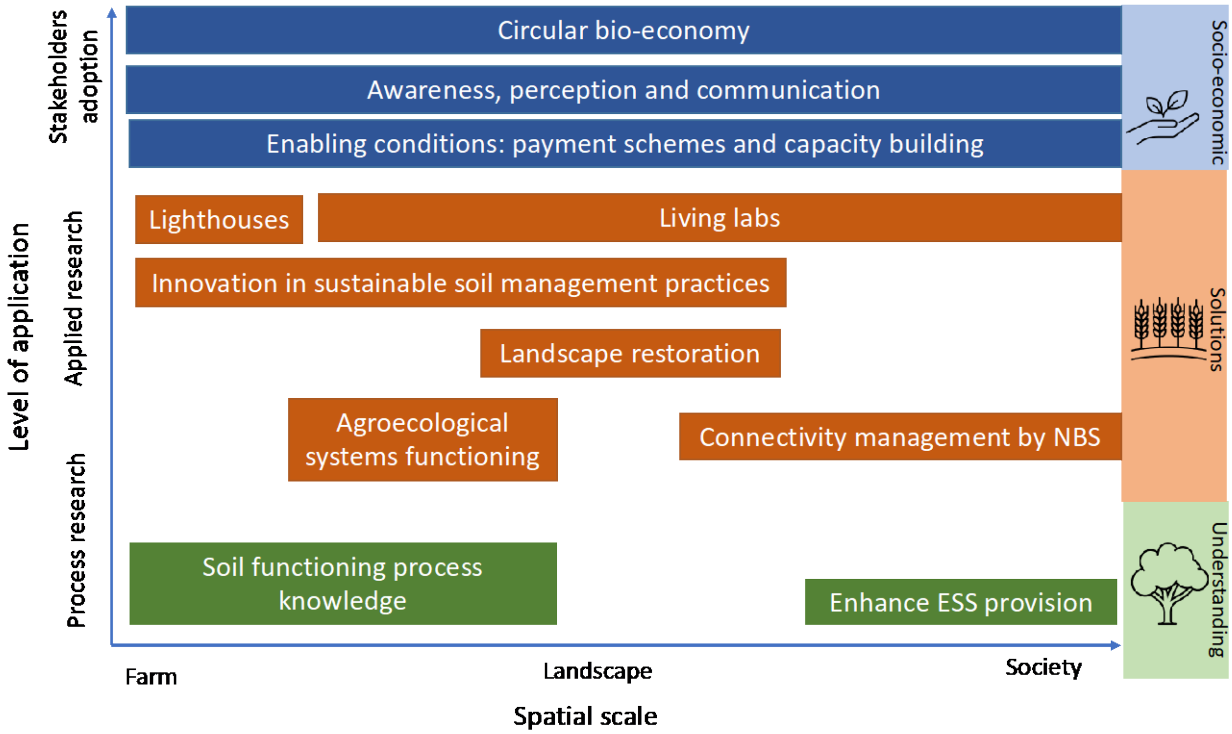



*Figure 4: Merging the objectives: diagram to depict the need of an integrated approach. The identified knowledge gaps have been placed in relation to both the level of application and the spatial scale (note NBS=Nature Based Solutions; ESS=Ecosystem services).*

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

### 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 the 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, Borelli 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 (Stolte et al., 2016; Keesstra et al., 2018).

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 (Smith, 2004; Lessmann et al., 2022; Chenu et al., 2019).

### Enhancing ecosystem services provision through soil health

In our knowledge gap analysis, the effect of complex interactions between cropping systems and the soil ecosystems was mentioned repeatedly. As was shown by Keesstra et al. (2016), there is a strong link between soil functions and ecosystem services (and the Sustainable Development Goals (SDGs) also). In another paper by Smith et al. (2021), the soil is shown to be essential for most of the '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 et al. (2018) further developed this link to show that soil functions are the basis under 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 essential is 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 Fig. 4)

Solid understanding of the natural system gained 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.

### Agroecological functioning

Nature-based solutions are often associated with large-scale interventions in coastal and river management. However, such solutions are very relevant in 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 phytofilters for small scale wastewater treatment, Keesstra et al., 2018a). 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 (Sonneveld et al., 2018; Mancuso et al., 2021; Miralles-Wilhelm, 2021). 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; soil ecosystem functioning. This systems understanding allows a more efficient and site-specific design of water and nutrient management.

## 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 (Arnaez 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 and 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 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 the smaller spatial scale restoration. Such restored landscapes also are 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 which extent crop choice (Cusworth et al., 2021), the implementation of agroforesty (Elevitch et al., 2018) and of 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 the success lies in merging farming and natural resource conservation (LaCanne and 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 the 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 Fig. 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.

### 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 a 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 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 $CO_2$ 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 program 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 subsidised while this induces massive erosion problems; 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.

**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 organisations like farm advisory services can play a crucial role. However, given the rapidly evolving agri-food sector and the focus on "demand-driven advise", technical capacity building also needs to take place within the advisory service is key for sustainable soil management (Ingram and 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.

**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 and 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 solution 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.
- A 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.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

## 6. References

Aasen, H., Honkavaara, E., Lucieer, A., Zarco-Tejada, P.J. (2018). Quantitative Remote Sensing at Ultra-High Resolution with UAV Spectroscopy: A Review of Sensor Technology, Measurement Procedures, and Data Correction Workflows. *Remote Sensing*, 10, 1091.

Amelung, W., Bossio, D., de Vries, W., Kogel-Knabner, I., Lehmann, J., Amundson, R., Bol, R., Collins, C., Lal, R., Leifeld, J., Minasny, B., Pan, G., Paustian, K., Rumpel, C., Sanderman, J., van Groenigen, J.W., Mooney, S., van Wesemael, B., Wander, M. & Chabbi, A. 2020. Towards a global-scale soil climate mitigation strategy. *Nature Communications*, 11, 5427.

Arnáez, J., Lana-Renaulta, N., Lasantab, T., Ruiz-Flañoa, P., Castroviejoa, J. (2015). Effects of farming terraces on hydrological and geomorphological processes. A review. *CATENA*, 128, 122-134.

Astover, A., Escuer-Gatius, J., Don, A., Armolaitis, K., Barančíková, G., Bolinder, M., Cornu, S., De Boever, M., Farina, R., Foldal, C., Jandl, R., Kasper, M., Fornara, D., Govednik, A., Mihelič, R., Vrščaj, B., Huyghebaert, B., Kasparinskis, R., Keel, S.G., László, P., Lehtonen, A., Madenoğlu, S., Maria da Conceição, G., Moni, C., O'Sullivan, L., Wall, D., Lanigan, G., Sánchez Gimeno, B., Taghizadeh-Toosi, A. (2021). Inventory of the use of models for accounting and policy support (soil quality and soil carbon). EJP SOIL Deliverable 2.12, 34 pp. https://ejpsoil.eu/fileadmin/projects/ejpsoil/WP2/Deliverable_2.12_Inventory_of_the_use_of_models_for_accounting_and_policy_support_-_soil_quality_and_soil_carbon.pdf

Bamière, L., Bellassen, V., Angers, D., Cardinael, R., Ceschia, E., Chenu, C., Constantin, J., Delame, N., Diallo, A., Graux, A.I., Houot, S., Klumpp, K., Launay, C., Letort, E., Martin, R., Meziere, D., Mosnier, C., Rechauchere, O., Schiavo, M., Therond, O. & Pellerin, S. 2023. A marginal abatement cost curve for climate change mitigation by additional carbon storage in French agricultural land. *Journal of Cleaner Production*, 383. 135423

Barbetti R. (2021). Low-cost digital mapping of soil organic carbon using optical spectrophotometer and Sentinel-2 image. *International Journal of Environmental Quality*, 44, 1-8.

Barbieri, P., Pellerin, S., Seufert, V., Smith, L., Ramankutty, N. & Nesme, T. 2021. Global option space for organic agriculture is delimited by nitrogen availability. *Nature Food*, **2,** 363-+.

Baulcombe, D., Crute, I., Davies, B., Dunwell, J., Gale, M., Jones, J., Pretty, J., Sutherland, W., Toulmin, C. (2009). Reaping the Benefits: Science and the Sustainable Intensification of Global Agriculture Royal Society, London.

Beillouin, D., Ben-Ari, T., & Makowski, D. (2019). Evidence map of crop diversification strategies at the global scale. *Environmental Research Letters*, 14(12), 123001.

Bellamy, P. H., Loveland, P. J., Bradley, R. I., Lark, R. M., & Kirk, G. J. (2005). Carbon losses from all soils across England and Wales 1978–2003. *Nature*, 437(7056), 245-248.

Borrelli, P., Alewell, C., Alvarez, P., Anache, J. A. A., Baartman, J., Ballabio, C., ... & Panagos, P. (2021). Soil erosion modelling: A global review and statistical analysis. *Science of the Total Environment*, 780, 146494.

Bossio D.A., Cook-Patton S.C., Ellis P.W., Fargione J., Sanderman J., Smith P., Wood S., Zomer R.J., Von Unger M., Emmer I.M., Griscom B.W. (2020). The role of soil carbon in natural climate solutions. *Nature Sustainability*, 3 (5), 391-398.

Bouwma I., Wigboldus S., Potters J., Selnes T., van Rooij S., Westerink J. (2022). Sustainability Transitions and the Contribution of Living Labs: A Framework to Assess Collective Capabilities and Contextual Performance. *Sustainability*, 14(23):15628.

Busse, M., Zhang, J., Fiddler, G., & Young, D. (2021). Compaction and organic matter retention in mixed-conifer forests of California: 20-year effects on soil physical and chemical health. *Forest Ecology and Management*, 482, 118851.

Cerdà, A., Ackermann, O., Terol, E., Rodrigo-Comino, J. (2019). Impact of farmland abandonment on water resources and soil conservation in citrus plantations in eastern Spain. *Water*, 11 (4), 824.

Cerdà, A., Franch-Pardo, I., Novara, A., Sannigrahi, S., & Rodrigo-Comino, J. (2022). Examining the effectiveness of catch crops as a nature-based solution to mitigate surface soil and water losses as an environmental regional concern. *Earth Systems and Environment*, 6(1), 29-44.

Cerdà, A., Lucas-Borja, M. E., Franch-Pardo, I., Úbeda, X., Novara, A., López-Vicente, M., ... & Pulido, M. (2021). The role of plant species on runoff and soil erosion in a Mediterranean shrubland. *Science of The Total Environment*, 799, 149218.

Cerdà, A., Rodrigo-Comino, J., Yakupoğlu, T., Dindaroğlu, T., Terol, E., Mora-Navarro, G., ... & Daliakopoulos, I. N. (2020). Tillage versus no-tillage. Soil properties and hydrology in an organic persimmon farm in Eastern Iberian Peninsula. *Water*, 12(6), 1539.

Chenu C., Angers D.A., Barré P., Derrien D., Arrouays D., Balesdent J. (2019). Increasing organic stocks in agricultural soils: Knowledge gaps and potential innovations. *Soil and Tillage Research*, 188, 41-52.
Chenu, C., Le Bissonnais, Y., Arrouays, D. (2000). Organic matter influence on clay wettability and soil aggregate stability. *Soil Science Society of America Journal*, 64(4), 1479-1486.
Clarke, D., Lázár, A. N., Saleh, A. F. M., & Jahiruddin, M. (2018). Prospects for agriculture under climate change and soil salinisation. In Ecosystem Services for Well-being in deltas, pp. 447-467. Palgrave Macmillan, Cham.
Cusworth, G., Garnett, T., Lorimer, J. (2021). Agroecological break out: Legumes, crop diversification and the regenerative futures of UK agriculture. *Journal of Rural Studies*, 88, 126–137.
De Notaris, C., Rasmussen, J., Sørensen, P., Olesen, J. E. (2018). Nitrogen leaching: A crop rotation perspective on the effect of N surplus, field management and use of catch crops. *Agriculture, Ecosystems & Environment,* 255, 1-11.
Di Prima, S., Rodrigo-Comino, J., Novara, A., Iovino, M., Pirastru, M., Keesstra, S., & Cerdà, A. (2018). Soil physical quality of citrus orchards under tillage, herbicide, and organic managements. *Pedosphere*, 28(3), 463-477.
Dignac, M.F., Derrien, D., Barre, P., Barot, S., Cecillon, L., Chenu, C., Chevallier, T., Freschet, G.T., Garnier, P., Guenet, B., Hedde, M., Klumpp, K., Lashermes, G., Maron, P.A., Nunan, N., Roumet, C. & Basile-Doelsch, I. 2017. Increasing soil carbon storage: mechanisms, effects of agricultural practices and proxies. A review. *Agronomy for Sustainable Development*, 37. 14
ECA (2018). European Court of Action Special report n°33/2018: Combating desertification in the EU: a growing threat in need of more action, 65 pp. https://op.europa.eu/webpub/eca/special-reports/desertification-33-2018/en/
ECA (2021). European Court of Action Special report 16/2021: Common Agricultural Policy and climate: Half of EU climate spending but farm emissions are not decreasing. 65 pp. https://www.eca.europa.eu/en/Pages/DocItem.aspx?did=58913
EEA (2015). Air quality in Europe – 2015 report. EEA Report 5/2015, European Environment Agency, Copenhagen. http://www.eea.europa.eu/publications/air-quality-in-europe-2015
EEA (2019). European Union emission inventory report 1990 — 201 under the UNECE Convention on Long-range Transboundary Air Pollution (LRTAP). EEA technical report No 9/2019. Copenhagen.http://www.eea.europa.eu/publications/eu-emission-inventory-report-lrtap
European Environment Agency, The European environment – state and outlook 2020 (EEA (2020) SOER), https://www.eea.europa.eu/soer/2020 (accessed 18 October 2021).
Elevitch, C. R., Mazaroli, D. N., & Ragone, D. (2018). Agroforestry standards for regenerative agriculture. Sustainability, 10(9), 3337.
European Commission (2017). Greening: a more complex income support scheme, not yet environmentally effective
European Commission (2018). In-Depth Analysis in Support of the Commission Communication COM(2018), 773: A Clean Planet for All - A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy. https://climate.ec.europa.eu/system/files/2018-11/com_2018_733_analysis_in_support_en.pdf
Regulation (EU) 2018/841 on the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry in the 2030 climate and energy framework. https://eur-lex.europa.eu/eli/reg/2018/841/2021-03-14.
European Commission (2019), Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, The European Green Deal, COM(2019) 640 final.
European Commission (2020). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. EU

Biodiversity Strategy for 2030 Bringing nature back into our lives, 22 pp. https://environment.ec.europa.eu/news/protecting-biodiversity-commission-advises-how-designate-additional-protected-areas-2022-01-28_en
European Commission (2021). Forging a climate-resilient Europe - the new EU Strategy on Adaptation to Climate Change. COM(2021), 82. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52021DC0082&from=EN.
European Commission (2021a). EU Soil Strategy for 2030, COM (2021), 699. https://ec.europa.eu/environment/publications/eu-soil-strategy-2030_en (2021)European Commission (2021b), Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of Regions, «Fit for 55»: Delivering the EU's 2030 Climate Target on the way to climate neutrality, COM (2021) 550 final of 14.07.2021, p. 1 ff.
European Commission (2022). Regulation of the Europan Parliament and of the Council establishing a Union certification framework for carbon removals {SEC(2022) 423 final} - {SWD(2022) 377 final} - {SWD(2022) 378 final}
European Commission. 2022. Regulation of the European Parliament and of the Euroean Council on nature restoration. COM(2022) 304 final. {SEC(2022) 256 final} - {SWD(2022) 167 final} - {SWD(2022) 168 final}.
FAO (2009). How to feed the World in 2050. Food and Agriculture Organization of the United Nations. Rome. www.fao.org/fileadmin/templates/wsfs/docs/expert_paper/How_to_Feed_the_World_in_2050.pdf
FAO (2017). Voluntary Guidelines for Sustainable Soil Management Food and Agriculture Organization of the United Nations. Rome, Italy.
FAO and ITPS (2015). Status of the World's Soil Resources (SWSR) – Main Report. Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils, Rome, Italy. http://www.fao.org/3/a-i5199e.pdf
Farina, R., Sándor, R., Abdalle, M., Álvaro-Fuentes, J., Bechini, L., Bolinder, M., Brilli, L., Chenu, C., Clivot, H., Migliorati, M., Di Bene, C., Dorich, C., Ehrhardt, F., Ferchaud, F., Fitton, N., Francaviglia, R., Franko, U., Giltrap, D., Grant, B., Bellocchi, G. (2021). Ensemble modelling, uncertainty and robust predictions of organic carbon in long-term bare-fallow soils. *Global Change Biology*, 27, 904-928.
Fogliatto, S., Ferrero, A. and Vidotto, F. (2020). Chapter Six - Current and future scenarios of glyphosate use in Europe: Are there alternatives? In Advances in Agronomy. D. L. Sparks, Academic Press. 163, 219-278.
Feng, T., Wei, W., Chen, L., Cerdà, A., Yang, L., Yu, Y. (2019). Combining land preparation and vegetation restoration for optimal soil eco-hydrological services in the Loess Plateau, China. *Science of The Total Environment,* 657, 535–547.
Fenster, T.L.D., Oikawa, P.Y., Lundgren, J.G. (2021). Regenerative Almond Production Systems Improve Soil Health, Biodiversity, and Profit. *Frontiers in Sustainable Food Systems*, 5.
Fetting, C. (2020). "The European Green Deal", ESDN Report, December 2020, ESDN Office, Vienna.
Franke, A. C., Kotzé, E. (2022). High-density grazing in southern Africa: Inspiration by nature leads to conservation? *Outlook on Agriculture*, 51(1), 67–74.
Fryirs, K.A., Brierley, G.J., Preston, N.J., Spencer, J. (2007). Catchment-scale (dis)connectivity in sediment flux in the upper Hunter catchment, New South Wales, Australia. *Geomorphology*, 84, 297.
Fuentes-Rodriguez, F., Juan, M., Gallego, I., Lusi, M., Fenoy, E., Leon, D., Penalver, P., Toja, J, Casas, J. J. (2013). Diversity in Mediterranean farm ponds: trade-offs and synergies between irrigation modernisation and biodiversity conservation. *Freshwater Biology*, 58(1), 63-78.

Fuller, I.C, Death, R.G. (2018). Integrating geomorphology and ecology for resilient river management in an era of global change. Proceedings 3rd International Conference, Integrative Sciences and Sustainable Development of Rivers, Lyon, 5-7. http://www.graie.org/ISRivers/docs/papers/2018/24B45-232FUL.pdf

Garnett T., Appleby M.C., Balmford A., Bateman I.J., Benton T.G., Bloomer P., Burlingame B., Dawkins M., Dolan L., Fraser D., Herrero M., Hoffmann I., Smith P., Thornton P.K., Toulmin C., Vermeulen S.J., Godfray H.C. (2013). Agriculture. Sustainable intensification in agriculture: premises and policies. *Science*, 341(6141), 33-34.

Gerhards, R. and Schappert, A. (2020). Advancing cover cropping in temperate integrated weed management. *Pest Management Science* 76(1), 42-46.Hansen, E. M., Munkholm, L.J., Olesen, J.E., Melander, B. (2015). Nitrate leaching, yields and carbon sequestration after noninversion tillage, catch crops, and straw retention. *Journal of Environmental Quality* 44(3), 868-881.

Giller, K. E., Hijbeek, R., Andersson, J. A., & Sumberg, J. (2021). Regenerative agriculture: An agronomic perspective. *Outlook on Agriculture*, 50(1), 13-25.

Gumiere, S.J., Bailly, J.-S., Cheviron, B., Raclot, D., Bissonnais, Y.L. & Rousseau, A.N. (2015). Evaluating the impact of the spatial distribution of land management practices on water erosion: Case study of a mediterranean catchment. *Journal of Hydrologic Engineering*, 20.

Gusli, S., Sumeni, S., Sabodin, R., Muqfi, I.H., Nur, M., Hairiah, K., Useng, D., van Noordwijk, M. (2020). Soil organic matter, mitigation of and adaptation to climate change in cocoa-based agroforestry systems. *Land*, 9.

Hansen, E.M., Munkholm, L.J., Olesen, J.E., Melander, B. (2015). Nitrate leaching, yields and carbon sequestration after noninversion tillage catch crops, and straw retention. *Journal of Environmental Quality*, 44, 868-881.

Hasler B., Termansen M., Nielsen H. Ø., Daugbjerg C., Wunder S., Latacz-Lohmann U. (2022). European Agri-Environmental Policy: Evolution, Effectiveness, and Challenges. *Review of Environmental Economics and Policy*, 16, 105–25.

Hassani, A., Azapagic, A., & Shokri, N. (2021). Global predictions of primary soil salinization under changing climate in the 21st century. *Nature Communications*, 12(1), 1-17.

Hauck, J., Schleyer, C., Priess, J.A., Veerkamp, C.J., Dunford, R., Alkemade, R., Berry, P., Primmer, E., Kok, M., Young, J., Haines-Young, R., Dick, J., Harrison, P.A., Bela, G., Vadineanu, A. & Gorg, C. 2019. Combining policy analyses, exploratory scenarios, and integrated modelling to assess land use policy options. *Environmental Science & Policy*, **94,** 202-210.

Heikkinen, J., Ketoja, E., Nuutinen, V., & Regina, K. (2013). Declining trend of carbon in Finnish cropland soils in 1974–2009. *Global change biology*, 19(5), 1456-1469.

Higgins, S., Z. Kadziuliene, Z., Paz, A., Mason, E., Vervuurt, W., Astover, A., Borchard, N., Jacobs, A., Laszio, P., Wall, D., Trinchera, G.A., Budai, A., Mano, R., Thorma, S., Rok, J.M., Sanchez, B., Hirte, J., Madenogiu, S. (2021). Stocktake study and recommendations for harmonizing methodologies for fertilization guidelines. EJP SOIL Deliverable D2.13, 30 pp. https://ejpsoil.eu/fileadmin/projects/ejpsoil/WP2/Deliverable_2.13_Stocktake_study_and_recommendations_for_harmonizing_methodologies_for_fertilization_guidelines.pdf

Higgins, S., Keesstra, S., Kadziuliene, Z., Jordan-Meille, L., Wall, D., Spiegel, H., Sanden, T., Baumgarten, A., Jensen, J., Hirte., J., Liebisch, F., Klages, S., Loew, P., Kuka, K., De Boever, M., D'Haene, K., Madenoglu, S., Özcan, H., Vervuurt, W., de Haan, J., Geel, W. van, Stenberg, B., Denoroy, P., Mihelič, R., Astover, A., Mano, R., Sempiterno, C., Calouro, F., Valboa, G., Aronsson, H., Krogstad, T., Torma, S, Gabriel, J., Laszlo, P., Borchard, N., Adamczyk, B., Jacobs, A., Jurga, B., Smreczak, B., Huyghebaert, B., Abras, M., Kasparinskis, R., Mason, E., Chenu, C., 2023. Stocktake study of current fertilisation recommendations across Europe and discussion towards a more harmonised approach. Accepted for publication.

Hofmeijer, M. A. J., Melander, B., Salonen, J., Lundkvist, A., Zarina, L., Gerowitt, B. (2021). Crop diversification affects weed communities and densities in organic spring cereal fields in northern Europe. *Agriculture, Ecosystems & Environment,* 308, 107251.
Hondebrink, M.A., Cammeraat, L.H., Cerdà, A. (2017). The impact of agricultural management on selected soil properties in citrus orchards in Eastern Spain: A comparison between conventional and organic citrus orchards with drip and flood irrigation. *Science of the Total Environment*, 581–582, 153–160.
Hossain, A., Krupnik, T. J., Timsina, J., Mahboob, M. G., Chaki, A. K., Farooq, M., Bhatt, R., Fahad, S., & Hasanuzzaman, M. (2020). Agricultural Land Degradation: Processes and Problems Undermining Future Food Security. In Environment, Climate, Plant and Vegetation Growth (pp. 17-61). (Environment, Climate, Plant and Vegetation Growth). Springer International Publishing.
Hulme, P. E. (2005). Adapting to climate change: is there scope for ecological management in the face of a global threat? *Journal of Applied ecology*, 42(5), 784-794.
Ingram, JA, Mills, J. 2019. Are advisory services “fit for purpose” to support sustainable soil management? An assessment of advice in Europe. Soil Use Manage, 35, 21– 31.
IPBES (2019). Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. E. S. Brondizio, J. Settele, S. Díaz, and H. T. Ngo (editors). IPBES secretariat, Bonn, Germany. 1148 pp. https://doi.org/10.5281/zenodo.3831673 Juerges, N., Hansjürgens, B. (2018). Soil governance in the transition towards a sustainable bioeconomy – A review. *Journal of Cleaner Production*, 170, 1628–1639.
IPCC, 2019: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]. https://www.ipcc.ch/srccl/download/
Jones, A.; Panagos, P.; Barcelo, S.; Bouraoui, F.; Bosco, C.; Dewitte, O.; Gardi, C.; Erhard, M.; Hervas de Diego, F.; Hiederer, R.; Jeffery, S.; et al. 2012. The State of Soil in Europe—A Contribution of the JRC to the European Environment Agency’s Environment State and Outlook Report—SOER 2010; Office for Official Publications of the European Communities: Luxembourg, p. 76.
Jordon, M.W., Smith, P., Long, P.R., Burkner, P.C., Petrokofsky, G. & Willis, K.J. 2022. Can Regenerative Agriculture increase national soil carbon stocks? Simulated country-scale adoption of reduced tillage, cover cropping, and ley-arable integration using RothC. *Science of the Total Environment*, **825**. 153955
Juerges, N., and Hansjürgens, B. (2018). Soil governance in the transition towards a sustainable bioeconomy – A review. *Journal of Cleaner Production*, 170, 1628-1639.
Juventia, S. D., Rossing, W. A., Ditzler, L., & van Apeldoorn, D. F. (2021). Spatial and genetic crop diversity support ecosystem service delivery: A case of yield and biocontrol in Dutch organic cabbage production. *Field Crops Research*, 261, 108015.
Kalantari, Z, Ferreira, C.S.S., Koutsouris, A.J., Ahlmer, A.K., Cerdà, A., Destouni, G. (2019). Assessing flood probability for transportation infrastructure based on catchment characteristics, sediment connectivity and remotely sensed soil moisture. *Science of the total environment*, 661, 393-406.
Keesstra, S.D., Bouma, J., Wallinga, J., Tittonell, P., Smith, P., Cerdà, A., Montanarella, L., Quinton, J.N., Pachepsky, Y., Van Der Putten, W.H., Bardgett, R.D., Moolenaar, S., Mol, G., Jansen, B., Fresco, L.O. (2016). The significance of soils and soil science towards realization of the United Nations sustainable development goals. SOIL, 2, 111-128.
Keesstra, S. D., Rodrigo-Comino, J., Novara, A., Giménez-Morera, A., Pulido, M., Di Prima, S., Cerdà, A. (2019). Straw mulch as a sustainable solution to decrease runoff and erosion in glyphosate-treated

clementine plantations in Eastern Spain. An assessment using rainfall simulation experiments. *Catena*, 174, 95-103.

Keesstra, S., Metze, T., Ofori, L., Buizer, M., & Visser, S. (2022). What Does the Circular Household of the Future Look Like? An Expert-Based Exploration. *Land*, 11(7), 1062.

Keesstra, S., Nunes, J., Novara, A., Finger, D., Avelar, D., Kalantari, Z., Cerdà, A. (2018a). The superior effect of nature based solutions in land management for enhancing ecosystem services. *Science of the Total Environment*, 610–611, 997–1009.

Keesstra, S., Nunes, J.P., Saco, P., Parsons, T., Poeppl, R., Masselink, R., Cerdà, A. (2018). The way forward: Can connectivity be useful to design better measuring and modelling schemes for water and sediment dynamics? *Science of the Total Environment*, 644, 1557-1572.

Keesstra, S., Pereira, P., Novara, A., Brevik, E.C., Azorin-Molina, C., Parras-Alcántara, L., Jordán, A., Cerdà, A. (2016). Effects of soil management techniques on soil water erosion in apricot orchards. *Science of the Total Environment*, 551–552, 357–366.

Keesstra, S., Visser, S., Cleen, M. (2021). Achieving Land Degradation Neutrality: A Robust Soil System Forms the Basis for Nature-Based Solutions. *Land*, 10, 1300.

Keesstra, S.D, Munkholm., L., Cornu, S., Visser, S.M., Faber., J., Kuikman, P., Thorsoe, M., de Haan, J., Vervuurt, W., Verhagen, J., Neumann, M., Fantappie, M., van Egmond, F., Bispo. A., Wall, D., Berggreen, L., Barron, J., Gascuel, C., Granjou, C., Gerasina, R., Chenu, C., 2020. https://ejpsoil.eu/fileadmin/projects/ejpsoil/WP2/Deliverable_2.4_Roadmap_for_the_European_Joint_Programme_SOIL.pdf

Köhler, J., Geels, F.W., Kern, F., Markard, J., Onsongo, E., Wieczorek, A., Alkemade, F., Avelino, F., Bergek, A., Boons, F., Fünfschilling, L., Hess, D., Holtz, G., Hyysalo, S., Jenkins, K., Kivimaa, P., Martiskainen, M., McMeekin, A., Mühlemeier, M.S., Nykvist, B., Pel, B., Raven, R., Rohracher, H., Sandén, B., Schot, J., Sovacool, B., Turnheim, B., Welch, D., Wells, P. (2019). An agenda for sustainability transitions research: State of the art and future directions. E*nvironmental Innovation and Societal Transitions*, 31, 1–32.

LaCanne, C. E., & Lundgren, J. G. (2018). Regenerative agriculture: merging farming and natural resource conservation profitably. *PeerJ*, 6, e4428.

Lafortezza, R., Chen, J., Van Den Bosch, C. K., & Randrup, T. B. (2018). Nature-based solutions for resilient landscapes and cities. Environmental research, 165, 431-441.

Lapierre, J., Machado, P.V.F., Debruyn, Z., Brown, S.E., Jordan, S., Berg, A., Biswas, A., Henry, H.A.L., Wagner-Riddle, C. (2022). Cover crop mixtures: A powerful strategy to reduce post-harvest surplus of soil nitrate and leaching. *Agriculture, Ecosystems & Environment,* 325, 107750.

Le Quéré C., Andrew R.M., Friedlingstein P., Sitch S., Hauck J., Pongratz J., Pickers P.A., Korsbakken J.I., Peters G.P., Canadell J.G., Arneth A., Arora V.K., Barbero L., Bastos A., Bopp L., Chevallier F., Chini L.P., Ciais P., Doney S.C., Gkritzalis T., Goll D.S., Harris I., Haverd V., Hoffman F.M., Hoppema M., Houghton R.A., Hurtt G., Ilyina T., Jain A.K., Johannessen T., Jones C.D., Kato E., Keeling R.F., Goldewijk K.K., Landschützer P., Lefèvre N., Lienert S., Liu Z., Lombardozzi D., Metzl N., Munro D.R., Nabel J.E.M.S., Nakaoka S.-I., Neill C., Olsen A., Ono T., Patra P., Peregon A., Peters W., Peylin P., Pfeil B., Pierrot D., Poulter B., Rehder G., Resplandy L., Robertson E., Rocher M., Rödenbeck C., Schuster U., Schwinger J., Séférian R., Skjelvan I., Steinhoff T., Sutton A., Tans P.P., Tian H., Tilbrook B., Tubiello F.N., Van Der Laan-Luijkx I.T., Van Der Werf G.R., Viovy N., Walker A.P., Wiltshire A.J., Wright R., Zaehle S., Zheng B. (2018). Global Carbon Budget 2018. *Earth System Science Data*, 10 (4), 2141-2194.

Lessmann, M., Ros, G. H., Young, M. D., & de Vries, W. (2022). Global variation in soil carbon sequestration potential through improved cropland management. *Global Change Biology*, 28(3), 1162-1177.

Levavasseur, F., Bailly, J.S., Lagacherie, P., Colin, F., Rabotin, M. (2012). Simulating the effects of spatial configurations of agricultural ditch drainage networks on surface runoff from agricultural catchments. *Hydrological Processes*, 26, 3393–3404.

Levavasseur, F., Lagacherie, P., Bailly, J.S., Biarnès, A., Colin, F. (2015). Spatial modeling of man-made drainage density of agricultural landscapes. *Journal of Land Use Science*, 10, 256–276.

Liu, Y., Miao, H. T., Chang, X., & Wu, G. L. (2019). Higher species diversity improves soil water infiltration capacity by increasing soil organic matter content in semiarid grasslands. *Land Degradation & Development*, 30(13), 1599-1606

Llena, M., Vericat, D., Cavalli, M. et al. (2019). The effects of land use and topographic changes on sediment connectivity in mountain catchments. *Science of the Total Environment*, 660, 899-912.

López-Vicente, M., Cerdà, A., Kramer, H., Keesstra, S. (2021). Post-fire practices benefits on vegetation recovery and soil conservation in a Mediterranean area. *Land Use Policy*, 111, 105776.

Lugato, E., Bampa, F., Panagos, P., Montanarella, L., Jones, A. (2014). Potential carbon sequestration of European arable soils estimated by modelling a comprehensive set of management practices. *Global Change Biology*, 20, 3557-3567.

Maharajan, T., Ceasar, S.A., Krishna, T.P.A., Ignacimuthu, S. (2021). Management of phosphorus nutrient amid climate change for sustainable agriculture. *Journal of Environmental Quality,* 50(6), 1303-1324.

Mancuso, G., Bencresciuto, G. F., Lavrnić, S., & Toscano, A. (2021). Diffuse water pollution from agriculture: A review of Nature-Based Solutions for nitrogen removal and recovery. *Water*, 13(14), 1893.

Melander, B, McCollough, M.R. (2020). Influence of intra-row cruciferous surrogate weed growth on crop yield in organic spring cereals. *Weed Research*, 60, 464– 474.

Mills, J., Gaskell, P., Ingram, J., Dwyer, J., Reed, M. & Short, C. (2017). Engaging farmers in environmental management through a better understanding of behaviour. *Agriculture and Human Values*, 34, 283–299.

Miralles-Wilhelm, F. (2021). Nature-based solutions in agriculture - Sustainable management and conservation of land, water and biodiversity. Virginia. FAO and The Nature Conservancy. https://doi.org/10.4060/cb3140en

Montanarella, L. and Panagos, P. (2021). The relevance of sustainable soil management within the European Green Deal, *Land Use Policy*, ISSN 0264-8377, 100, 104950.

Morvan, X., Verbeke, L., Laratte, S., Schneider, A. R. (2018). Impact of recent conversion to organic farming on physical properties and their consequences on runoff, erosion and crusting in a silty soil. *Catena*, 165, 398-407.

Munkholm, L.J., Zechmeister-Boltenstern, S. (2021). Set of reports on State of knowledge in agricultural soil management Deliverable D2.6. EJP SOIL Report WP2 (H2020-SFS-2018 – 2020/H2020SFS-2019 – 1, GA 862695), 110 pp. https://ejpsoil.eu/fileadmin/projects/ejpsoil/WP2/Deliverable_D2.6_Set_of_reports_on_State_of_knowledge_in_agricultural_soil_management.pdf

Muscat, A., de Olde, E. M., Ripoll-Bosch, R., Van Zanten, H. H., Metze, T. A., Termeer, C. J., ... & de Boer, I. J. (2021). Principles, drivers and opportunities of a circular bioeconomy. *Nature Food*, 2(8), 561-566.

Nevalainen, O., Niemitalo, O., Fer, I., Juntunen, A., Mattila, T., Koskela, O., Kukkamäki, J., Höckerstedt, L., Mäkelä, L., Jarva, P. and Heimsch, L. (2022). Towards agricultural soil carbon monitoring, reporting, and verification through the Field Observatory Network (FiON). *Geoscientific Instrumentation, Methods and Data Systems*, 11(1), 93-109.

Nocita, M., Stevens, A., Van Wesemael, B., Aitkenhead, M., Bachmann, M., Barthès, B., Ben Dor, E., Brown, D.J., Clairotte, M., Csorba, A., Dardenne, P., Demattê, J.a.M., Genot, V., Guerrero, C., Knadel, M., Montanarella, L., Noon, C., Ramirez-Lopez, L., Robertson, J., Sakai, H., Soriano-Disla, J.M., Shepherd, K.D., Stenberg, B., Towett, E.K., Vargas, R., Wetterlind, J. (2015). Soil Spectroscopy: An Alternative to Wet Chemistry for Soil Monitoring. In Advances in Agronomy. Sparks D.L., 139-159.

Novara, A., Pulido, M., Rodrigo-Comino, J., Prima, S.D.I., Smith, P., Gristina, L., Giménez-Morera, A., Terol, E., Salesa, D., Keesstra, S. (2019). Long-term organic farming on a citrus plantation results in soil organic carbon recovery. *Cuadernos de Investigación Geográfica*, 45(1), 271-286. https://doi.org/10.18172/cig.3794.

Panagos, P., Standardi, G., Borrelli, P., Lugato, E., Montanarella, L., & Bosello, F. (2018). Cost of agricultural productivity loss due to soil erosion in the European Union: From direct cost evaluation approaches to the use of macroeconomic models. *Land Degradation & Development*, 29(3), 471-484.

Pavlů, L., Sobocká, J., Borůvka, L., Penížek, V., Adamczyk, B., Baumgarten, A., Castro, I.V., Cornu, S., De Boever, M., Don, A., Feiziene, D., Garland, G., Gimeno, B.S., Grčman, H., Hawotte, F., Higgins, A., Kasparinskis, R., Kasper, M., Kukk, L., Laszlo, P., Madenoğlu, S., Meurer, K., Schjønning, P., Skaalsveen, K., O'Sullivan, L., Vanino, S., Vervuurt, W., Wawer, R. (2021). Towards climate-smart sustainable management of agricultural soils: EJP SOIL Deliverable 2.2 Stocktaking on soil quality indicators and associated decision support tools, including ICT tools. Report, 97 pp. https://edepot.wur.nl/563875

Paz, A., Carranca, C., Miloczki, J., Gonçalves, M.C., Castanheira, N., Mihelič,R., Carrasco, M., Vicente, C., Don, A., Vrščaj, B., Sanchez, B., Huyghebaert, B., Stajnko, D., Intrigliolo, D.S., Mason, E., Garland, G., Känkänen, H., Spiegel, H., Castro, I., Lesjak, J., de Haan, J., Mellon, J., Vilcek, J., Miloczki, J., Skaalsveen, K., Meurer, K., Sándor, K., Munkholm, L., Kukk, L., de Boever, M., Pulido-Moncada, M., Nino, P., R. Ramsey, R., Wawer, R., Kasparinskis, R., Madenoğlu, S., Higgins, S., Salo, T., Feiza, V., Penizek, V., Vervuurt, W. (2021). EJP SOIL Deliverable D2.1: Synthesis of the impact of sustainable soil management practices in Europe, 80 pp. https://ejpsoil.eu/fileadmin/projects/ejpsoil/WP2/Deliverable_2.1_Synthesis_of_the_impact_of_sustainable_soil_management_practices_in_Europe.pdf

Pellerin, S., Bamière, L., Angers, D., Béline, F., Benoit, M., Butault, J.-P., Chenu, C., Colnenne-David, C., De Cara, S, Delame, N., Doreau, M., Dupraz, P., Faverdin, P., Garcia-Launay, F., Hassouna, M., Hénault, C., Jeuffroy, M.-H., Klumpp, K., Metay, A., Moran, D., Recous, S., Samson, E., Savini, I., Pardon, L., Chemineau, P. (2017). Identifying cost-competitive greenhouse gas mitigation potential of French agriculture. *Environmental Science & Policy*, 77, 130-139.

Perignon, P., Vieux, F., Soler, L.-G., Masset, G., Darmon, N. (2017). Improving diet sustainability through evolution of food choices: review of epidemiological studies on the environmental impact of diets. *Nutrition Reviews*, 75, 2–17.

Puy, A., Avilés, J. M. G., Balbo, A. L., Keller, M., Riedesel, S., Blum, D., & Bubenzer, O. (2017). Drip irrigation uptake in traditional irrigated fields: The edaphological impact. *Journal of Environmental Management*, 202, 550-561.

Pulido, F. J., Díaz, M., & de Trucios, S. J. H. (2001). Size structure and regeneration of Spanish holm oak Quercus ilex forests and dehesas: effects of agroforestry use on their long-term sustainability. *Forest Ecology and Management*, 146(1-3), 1-13.

Rana, J., Paul, J. (2017). Consumer behavior and purchase intention for organic food: A review and research agenda. *Journal of Retailing and Consumer Services*, 38, 157-165.

Rodrigo-Comino, J., López-Vicente, M., Kumar, V., et al. (2020). Soil Science Challenges in a New Era: A Transdisciplinary Overview of Relevant Topics. *Air, Soil and Water Research*, 13. https://doi.org/10.1177/1178622120977491

Rodrigues, L., Fohrafellner, J., Hardy, B., Huyghebaert, B., Leifeld, J., Cobeña, A.S., Budai A., Lazdiņš A., ... & Gergely, T. (2021). Towards climate-smart sustainable management of agricultural soils. Deliverable 2.3: Synthesis on estimates of achievable soil carbon sequestration on agricutural land across Europe. Report, 84 pp. https://ejpsoil.eu/fileadmin/projects/ejpsoil/WP2/Deliverable_2.3_Synthesis_on_estimates_of_achievable_soil_carbon_sequestration_on_agricutural_land_across_Europe_Updated_20210615.pdf

Rodrigues, L., Hardy, B., Huygheb eart, B., Fohrafellner, J., Fornara, D., Barančíková, G., Bárcena, T.G., De Boever, M., Di Bene, C., Feizienė, D., Käetterer, T., Laszlo, P., O'Sullivan, L., Seitz, D., Leifeld, J. (2021). Achievable agricultural soil carbon sequestration across Europe from country-specific estimates. *Global Change Biology*, 27: (24), 6363–6380.

Rolo, V., Hartel, T., Aviron, S., Berg, S., Crous-Duran, J., Franca, A., ... & Moreno, G. (2020). Challenges and innovations for improving the sustainability of European agroforestry systems of high nature and cultural value: stakeholder perspectives. *Sustainability Science*, 15(5), 1301-1315.

Runge, T., Latacz-Lohmann, U., Schaller, L., Todorova, K., Daugbjerg, C., Termansen, M., Liira, J., Le Gloux, F., Dupraz, P., Leppanen, J., Fogarasi, J., Vigh, E.Z., Bradfield, T., Hennessy, T., Targetti, S., Viaggi, D., Berzina, I., Schulp, C., Majewski, E., Bouriaud, L., Baciu, G., Pecurul, M., Prokofieva, I. and Velazquez, F.J.B. (2022). Implementation of Eco-schemes in Fifteen European Union Member States. *EuroChoices*, 21, 19-27.

Ruysschaert, G., Jacob, M., Munkholm, L.J, Thorsøe, M., Farina, R., Marandola. D., Di Bene, C., Piccini, Ch, Vanino, S., O'Sullivan, L., Wall, D., Keesstra. S. (2020). Toward a roadmap for EU Agricultural Soil Management. EJP SOIL Guidelines for the national input of work package 2 – task 2.1 – 2.2 – 2.3.

Saco, P.M., Rodríguez, J.F., Moreno-de las Heras, M., Keesstra, S., Azadi, S., Sandi, S., Baartman, J., Rodrigo-Comino, J., Rossi, M.J. (2020). Using hydrological connectivity to detect transitions and degradation thresholds: Applications to dryland systems. *CATENA*, 186, 104354.

Sanderman, J., Hengl, T., Fiske, G.J. (2017). Soil carbon debt of 12,000 years of human land use. *PNAS*, 114 9575-9580.

Schjønning, P. (2023). An empirical model for prediction of topsoil deformation in field traffic [Article]. Soil and Tillage Research, 227, Article 105589.

Schreefel, L., Schulte, R. P. O., De Boer, I. J. M., Schrijver, A. P., & Van Zanten, H. H. E. (2020). Regenerative agriculture–the soil is the base. *Global Food Security*, 26, 100404.

Sharma, G., Shrestha, S., Kunwar, S., Tseng, T.-M. (2021). Crop Diversification for Improved Weed Management: A Review. *Agriculture* 11(5), 461.

Smith, P. (2004). Carbon sequestration in croplands: the potential in Europe and the global context. *European Journal of Agronomy*, 20(3), 229-236.

Smith, P., Keesstra, S. D., Silver, W. L., & Adhya, T. K. (2021). The role of soils in delivering Nature's Contributions to People. *Philosophical Transactions of the Royal Society B*, 376(1834), 20200169.

Smith P, Martinio D, Cai Z et al. (2008). Greenhouse gas mitigation in agriculture. *Philosophiocal Transactions of the Royal Society B*, 363, 789–813.

Smith, P., Soussana, J.F., Angers, D., Schipper, L., Chenu, C., Rasse, D.P., Batjes, N.H., Van Egmond, F., Mcneill, S., Kuhnert, M., Arias-Navarro, C., Olesen, J.E., Chirinda, N., Fornara, D., Wollenberg, E., Alvaro-Fuentes, J., Sanz-Cobena, A., Klumpp, K. (2020). How to measure, report and verify soil carbon change to realize the potential of soil carbon sequestration for atmospheric greenhouse gas removal. *Global Change Biology*, 26 (1), 219-241.

Sonneveld, B. G., Merbis, M. D., Alfarra, A., Ünver, O., & Arnal, M. F. (2018). Nature-based solutions for agricultural water management and food security. *FAO Land and Water Discussion Paper*, no. 12. Rome, FAO. 66 pp.

Stolte, J., Tesfai, M., Øygarden, L., Kværnø, S., Keizer, J., Verheijen, F., Panagos, P., Ballabio, C., Hessel, R. (2016). Soil threats in Europe: Status, methods, drivers and effects on ecosystem services. JRC Tecnical Reports, EUR 27607 EN; doi:10.2788/828742.

Taghizadeh-Toosi, A., Olesen, J. E., Kristensen, K., Elsgaard, L., Østergaard, H. S., Lægdsmand, M., ... & Christensen, B. T. (2014). Changes in carbon stocks of Danish agricultural mineral soils between 1986 and 2009. *European Journal of Soil Science*, 65(5), 730-740.

Tahat, M., Alananbeh, K.M., Othman, Y.A., Leskovar, D.I. (2020). Soil Health and Sustainable Agriculture. *Sustainability,* 12(12), 4859.

Taylor, A., Wynants, M., Munishi, L., Kelly, C., Mtei, K., Mkilema, F., Ndakidemi, P., Nasseri, M., Kalnins, A., Patrick, A., Gilvear, D., Blake, W. (2021). Building climate change adaptation and resilience through soil organic carbon restoration in sub-saharan rural communities: Challenges and opportunities. *Sustainability*, 13, 10966.

Tiessen, H., Cuevas, E. and Chacon, P. (1994). The role of soil organic matter in sustaining soil fertility. *Nature*, 371(6500), 783-785.

Thorsøe, M.H., Keesstra, S.D., Jacobs, A., Piuccini, C., Fornara, D., Mason, E., Vanwindekens , F., Bøe, F., Siebielec, G., Fohrafellner, J., Meurer, K., Vervuurt, W. (2021). Report on the current availability and use of soil knowledge. EJP SOIL Deliverable D2.7, 122p. https://edepot.wur.nl/563850

Thorsøe, M.H., Noe, E.B., Lamandé, M., Frelih-Larsen, A., Kjeldsen, C., Zandersen, M., Schjønning, P. (2019). Sustainable soil management – Farmers' perspectives on subsoil compaction and the opportunities and barriers for intervention. *Land Use Policy*, 86, 427-437.

Thorsøe, M.H., Zechmeister-Boltenstern, S., Fohrafellner, J., Pulidomoncada, M., Munkholm, L. (2022). 1s6a: Enabling conditions for climate-smart sustainable management of agricultural soils. Abstract of the Conference Circular@WUR: Living within planetary boundaries, 11-13 April 2022, Wageningen. DOI 10.18174/567297

Ulén, P.S., B., Aronsson, H., Bechmann, M., Krogstad, T., Øygarden, L., Stenberg, M. (2010). Soil tillage methods to control phosphorus loss and potential side-effects: A Scandinavian review. *Soil Use and Management,* 26(2), 94-107.

Uniated Nations (2015). Global Sustainable Development Report. https://www.un.org/en/development/desa/publications/global-sustainable-development-report-2015-edition.html

Vanino, S., Pirelli, T., Di Bene, C., Bøe, F., Castanheira, N., Chenu, C., ... & Farina, R. (2023). Barriers and opportunities of soil knowledge to address soil challenges: Stakeholders' perspectives across Europe. *Journal of Environmental Management*, 325, 116581.

Van Rooij, S., Timmermans, W., Roosenschoon, O., Keesstra, S., Sterk, M., Pedroli, B. (2021). Landscape-based visions as powerful boundary objects in spatial planning: Lessons from three dutch projects. *Land,* 10, 1–14.

Vaudour, E., Gholizadeh, A., Castaldi, F., Saberioon, M., Borůvka, L., Urbina-Salazar, D., Fouad, Y., Arrouays, D., Richer-De-forges, A.C., Biney, J., Wetterlind, J. & van Wesemael, B. (2022). Satellite Imagery to Map Topsoil Organic Carbon Content over Cultivated Areas: An Overview. *Remote Sensing*, 14, 2917.

Veerman, C., Pinto Correia, T., Bastioli, C., Biro, B., Bouma, J., Cienciala, E., Emmett, B., Frison, E.A., Grand, A., Hristov, L. et al. (2020). 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 (EC), Luxembourg.

Visser, S., Keesstra, S., Maas, G., de Cleen, M., Molenaar, C. (2019). Soil as a Basis to Create Enabling Conditions for Transitions Towards Sustainable Land Management as a Key to Achieve the SDGs by 2030. *Sustainability*, 11, 6792.

Vrolijk, H., Reijs, J., & Dijkshoorn-Dekker, M. (2020). Towards sustainable and circular farming in the Netherlands: Lessons from the socio-economic perspective. Wageningen Economic Research. https://edepot.wur.nl/533842

Wiesmeier, M., Mayer, S., Burmeister, J., Hübner, R. & Kögel-Knabner, I. 2020. Feasibility of the 4 per 1000 initiative in Bavaria: A reality check of agricultural soil management and carbon sequestration scenarios. *Geoderma*, **369**.

Wiesmeier, M., Urbanski, L., Hobley, E., Lang, B., von Lutzow, M., Marin-Spiotta, E., van Wesemael, B., Rabot, E., Liess, M., Garcia-Franco, N., Wollschlager, U., Vogel, H.J. & Kogel-Knabner, I. 2019. Soil organic carbon storage as a key function of soils - A review of drivers and indicators at various scales. *Geoderma*, **333,** 149-162.

Zhang, J., Heijden, M. G., Zhang, F., Bender, S. F. (2020). Soil biodiversity and crop diversification are vital components of healthy soils and agricultural sustainability. *Frontiers of Agricultural Science and Engineering*, 7(3), 236.