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Towards climate-smart sustainable management of agricultural soils

Deliverable D2.6

Set of reports on State of knowledge in agricultural soil management

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ABSTRACT

For the advancement of climate-smart sustainable management of agricultural soils, we have to know more about three major topics of soil research, namely 1. Soil carbon stocks, 2. Soil degradation and fertility, and 3. Strategies for improved soil management. This report addresses state-of-the-art knowledge on these topics by bringing together the expertise of 254 members of the EJP SOIL consortium and by reviewing more than 1,800 documents. Based on this aggregation of available knowledge we identify major knowledge gaps raised by several authors.

Regarding the first topic, 'Carbon stocks', the analysis of European literature and national inputs identified the following main knowledge needs: Assessment and mapping of SOC under various management practices as well as life cycle assessment of management options beyond farm scale; the effect of C-enhancing management measures on GHG emissions; standardised approaches for SOC assessment across nations; the influence of management and environmental factors on deep soil carbon; SOC spatial and temporal dynamics; more information on SOC sequestration potentials of different soils across Europe; monitoring of SOC changes in long-term field experiments; the impacts of policies on C sequestration and means of transfer of information to relevant stakeholders; mapping peatlands and estimating their SOC stocks.

Regarding 'Soil degradation and fertility' the following knowledge needs were revealed by the review of national inputs as well as by EU projects and literature: Modelling and monitoring changes in SOC at different scales and climates; soil mineral SOC interaction in relation to soil structure, productivity and soil nutrients; impact of field traffic and livestock trampling on soil structure; soil functions and plant growth in different pedo-climatic zones; development of engineering solutions to limit risk of compaction; assessment of soil compaction impact in a changing climate and regulation measures to prevent soil structure degradation; improved monitoring programmes for wind, water and tillage erosion; development of site-specific soil erosion models and improved validation of the models; monitoring programmes and harmonised monitoring systems for pollutants; optimizing the use of plants for remediation of contaminated soils and the need for long-term soil remediation experiments; monitoring programmes of soil salinization and the impact of climate change on salinization risk; quantification of soil sealing; and, finally, systematic monitoring of soil acidification on non-forest soil.

For the topic 'Strategies for improved soil management', numerous knowledge needs have been mentioned, such as: Monitoring programmes for different soil parameters to be used for soil sustainable management decisions; monitoring and modelling sustainable soil management practices at a site-specific level under different climate change scenarios; need for a common conceptual understanding of crop/cover crop rotations and the effects of diversification – to be created at cultivar and genetic level; spatial and temporal dynamics of C and nutrients in the soil-plant-atmosphere system; multidisciplinary/comprehensive studies of cover cropping, intercropping and perennial cropping under different pedo-climatic conditions and with consideration for climate change; assessment of the effect of different organic amendments on soil C storage, GHG emissions, productivity, nutrient losses, water availability and soil quality; assessment of management practices to mitigate subsoil compaction and practices for efficient water management (site-specific) in a changing climate.

For all of the three addressed topics, more specific knowledge gaps were identified either from the European projects and literature or from the national inputs. In a general analysis of the three topics, peatlands, models and monitoring, and soil compaction were overarching issues, which demand assessment and improved management. The need for harmonised soil data and aligned monitoring programmes were also identified as key issues.

This report provides a list of important general and specific aspects within the three addressed topics, which are fundamental for setting the targets for the EJP SOIL research roadmap.

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List of acronyms and abbreviations

AT	Austria
BE-VLG	Belgium-Flanders
BE-WAL	Belgium-Wallonia
C	Carbon
CH	Switzerland
CZ	Czech Republic
DE	Germany
DK	Denmark
EE	Estonia
ES	Spain
EU	European Union
FL	Finland
FR	France
GHG	Greenhouse gas
HU	Hungary
IE	Ireland
IT	Italy
LT	Lithuania
LV	Latvia
NL	the Netherlands
NO	Norway
PL	Poland
PT	Portugal
SE	Sweden
SI	Slovenia
SK	Slovakia
SOC	Soil organic carbon
TR	Turkey
UK	the United Kingdom
FAO	Food and Agriculture Organization
ISO	International Organization for Standardization

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1 Introduction

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The aim of this report is to provide state-of-the-art knowledge of soil research within the EJP SOIL concept framework (Figure 1) to be used for revising the EJP SOIL research roadmap. EJP SOIL is a European Joint Programme Cofund on Agricultural Soil Management contributing to key societal challenges including climate change, water and future food security (https://projects.au.dk/ejpsoil/). The objectives are to develop knowledge, tools and an integrated research community to foster climate-smart sustainable agricultural soil management. The report is a part in a series of stocktakes within the EJP SOIL Work Package 2 that inform the work on a roadmap for EU Agricultural Soil Management. The other deliverables include a report that identifies current policy ambitions and future soil aspirational goals (task 2.1) and a report that identifies knowledge use (stakeholders' perspectives) (task 2.2.2), as well as an identification of barriers and opportunities by scenario development (task 2.3). Although each has a different focus, these reports are all based on feedback from a national group of researchers and stakeholders. Thus, there has been a special focus on identifying soil research knowledge gaps. This report primarily concerns the knowledge development compartment of the EJP SOIL knowledge framework (Figure 2). The work has, however, also included significant knowledge sharing and transfer elements through stakeholder participation, knowledge synthesis and dissemination/outreach. As outlined in the EJP SOIL annual plan, the objective for task 2.2.1 was to deliver a report addressing state-of-the-art knowledge of soil research on: 1. Carbon stock, 2. Soil degradation and fertility, and 3. Strategies for improved soil management. 'Carbon stock' relates to state-of-the-art knowledge on soil carbon monitoring and modelling, i.e., soil carbon seen from the carbon sequestration and climate regulation point of view. For the topic of 'Soil degradation and fertility', the related soil challenges and soil functions (except carbon sequestration and climate regulation) are listed in Figure 1. 'Strategies for improved soil management' relate to management options for Climate-Smart Sustainable Soil Management with offset in the Farm management categories listed in Figure 1.

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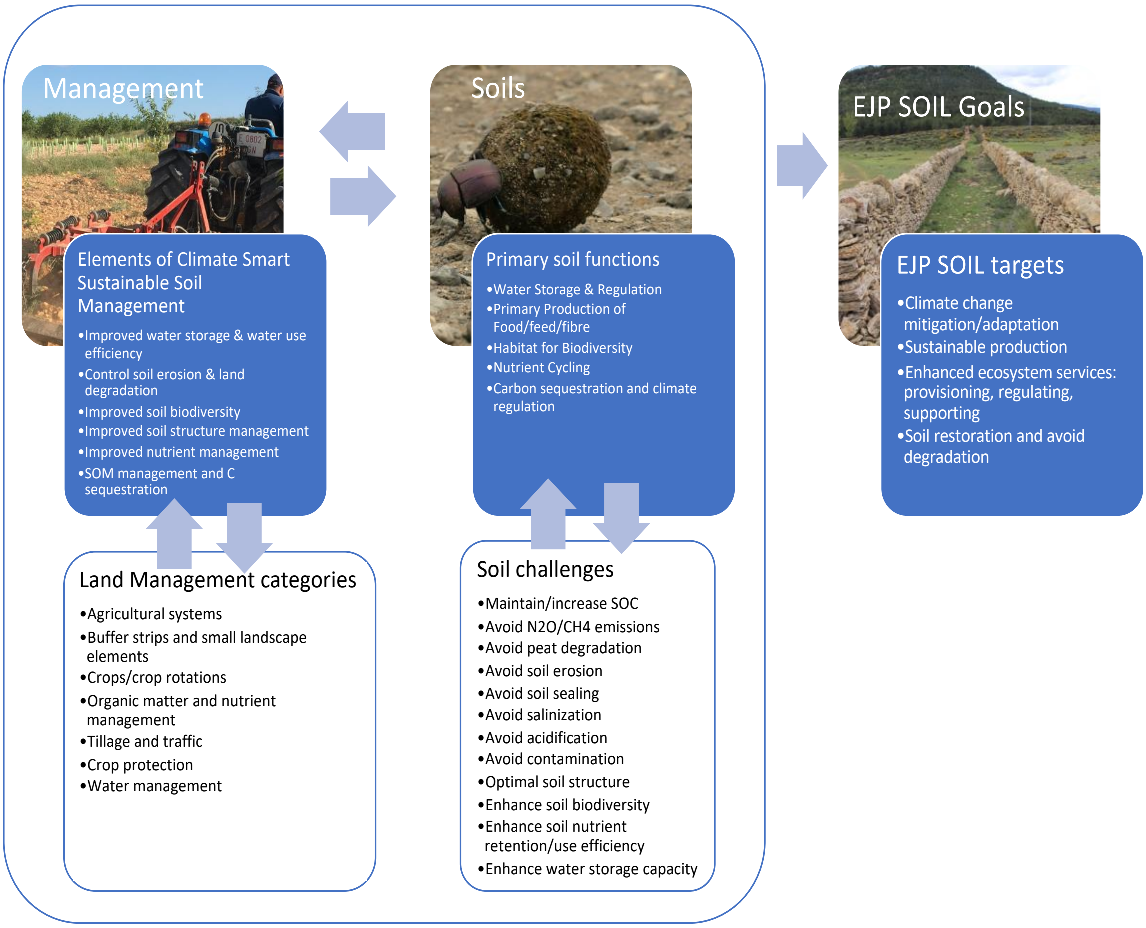

Figure 1. Soil Concept Framework: This linkages diagram illustrates how local land management choices can influence the elements defining climate-smart sustainable soil management. Secondly, the diagram shows the interlinkage between the primary soil functions and soil challenges, and that the local soil conditions both impact and are impacted by the management choices made for a specific location (Ruysschaert et al., 2020).

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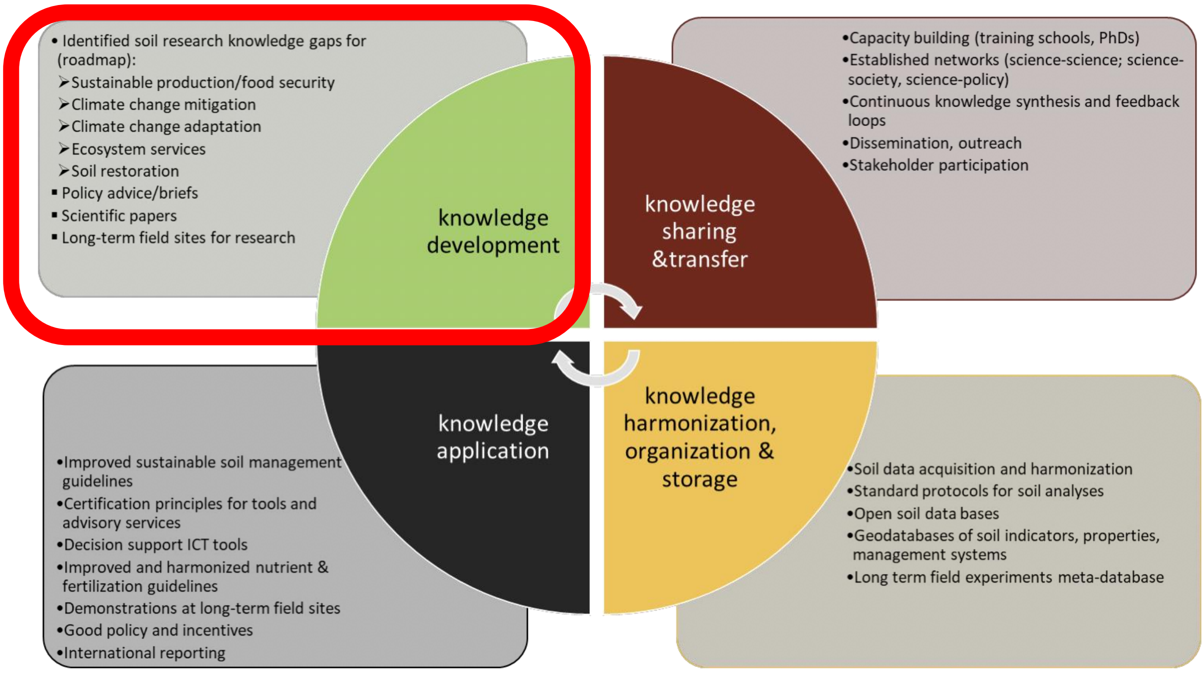

Figure 2. *EJP SOIL Knowledge framework.*

1.1 Methodology

The outlined work consisted of: 1. A review of the outputs of completed and ongoing EU projects, 2. Interviews with key stakeholders and project owners identified by the national hubs to give insights into the available knowledge and knowledge gaps and 3. Identification and review of strategic documents, reports and scientific literature of relevance for the status of European soils and their management. The latter was split into two so that the review of pan-European studies was conducted in relation to the review of completed and ongoing EU projects, whereas the review of national literature was carried out by the individual EJP SOIL partners in relation to the interviews with the national hubs. This report is based on inputs from 24 EJP SOIL partners representing 23 countries.

This report contains general information and data of the different soil challenges the countries face with regard to the state-of-the-art knowledge and knowledge gaps on: 1. Carbon stock, 2. Soil degradation and fertility, and 3. Strategies for improved soil management. To make the acquired information spatially explicit, we asked the partners for information according to the map of environmental zones (Metzger, 2005) shown in Figure 3. However, hardly any partner provided such details. Therefore, for the analysis of the national inputs, we applied a more simplified map (Figure 4) where Europe is divided into four regions: North, South, Central and West. In this report, the Northern region is represented by Denmark (DK), Estonia (EE), Finland (FI), Latvia (LV), Lithuania (LT), Norway (NO), and Sweden (SE); the Southern region by Italy (IT), Portugal (PT), Spain (ES) and Turkey (TR); the Central region by Austria (AT), Czech Republic (CZ), Germany (DE), Hungary (HU), Poland (PL), Slovakia (SK), Slovenia (SI), and Switzerland (CH); and the Western region by Belgium-Flanders (BE-VLG), Belgium-Wallonia (BE-WAL), France (FR), Ireland (IE), the Netherlands (NL), and the United Kingdom (UK).

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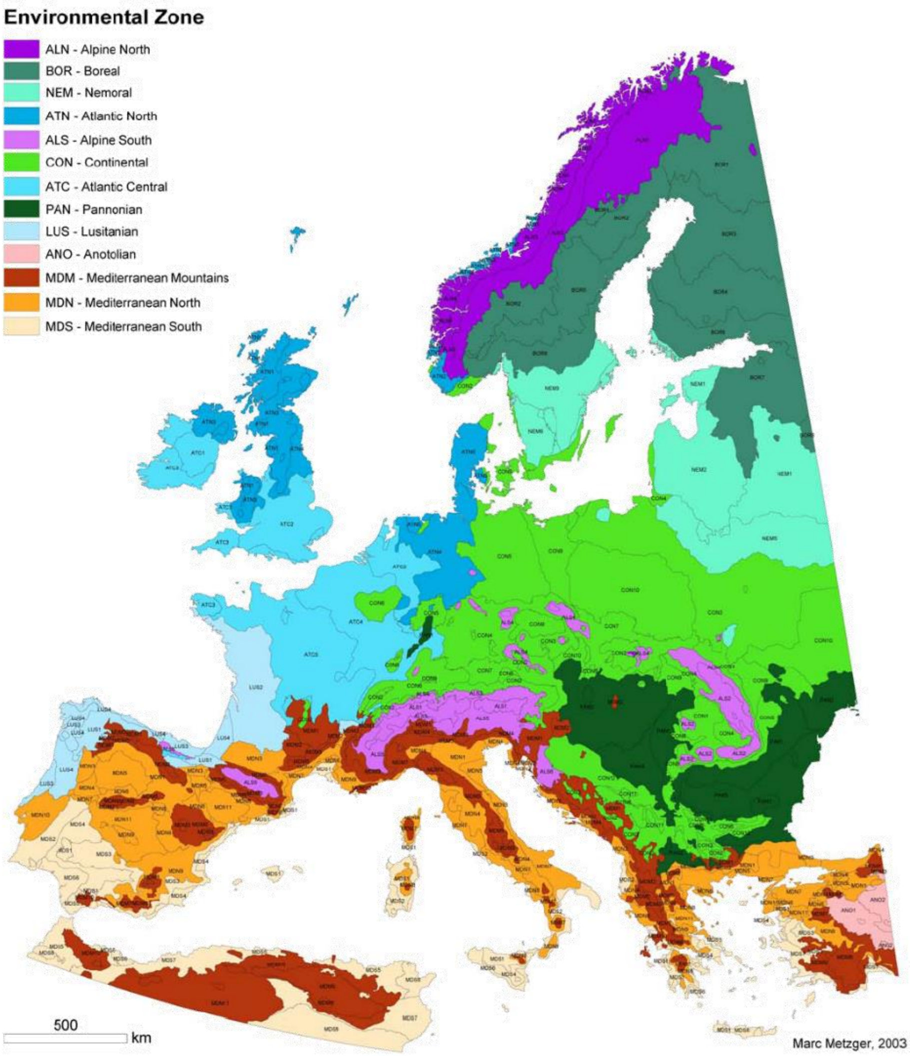

Figure 3. Environmental zones of Europe: Alpine North; Boral; Nemorial; Atlantic North, Atlantic South; Alpine South; Continental; Atlantic Central; Pannonian; Lusitanian; Anotolian; Mediterranean Mountains; Mediterranean North; Mediterranean South.

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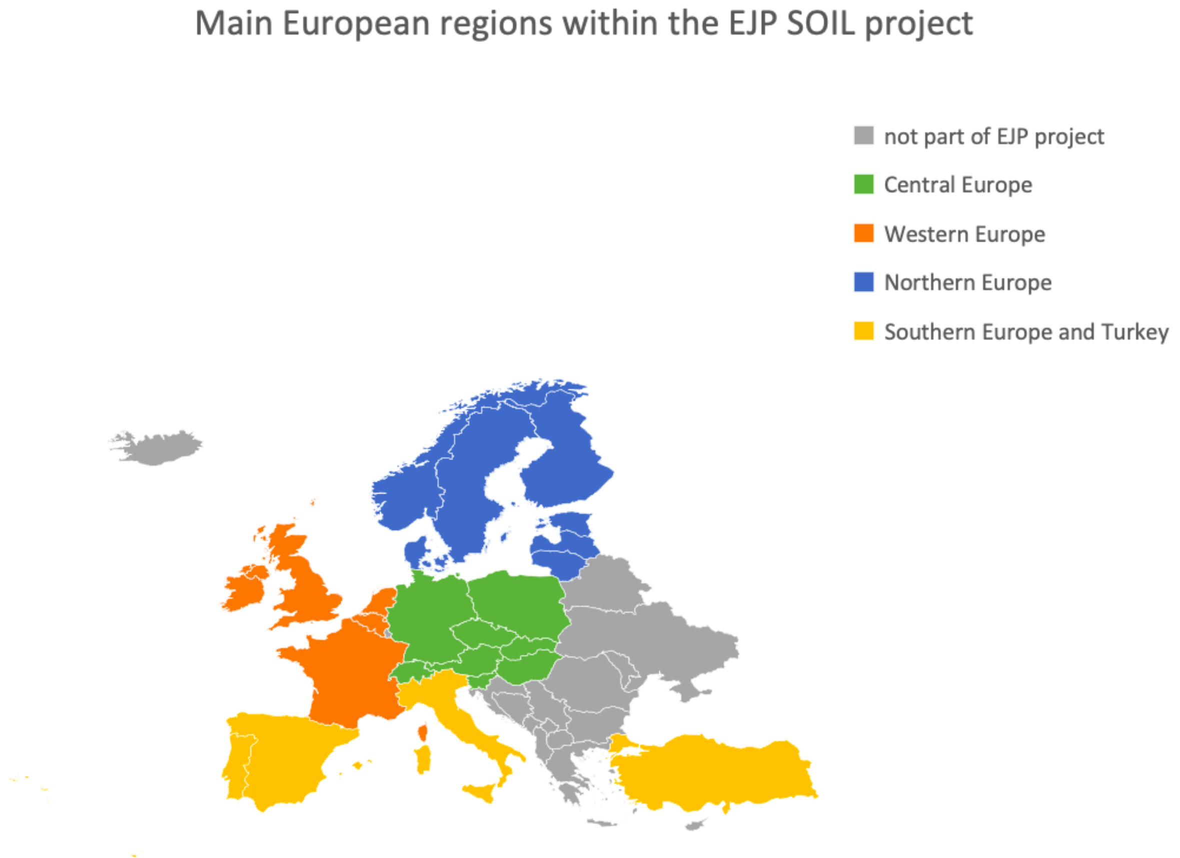

Figure 4. Main European regions within the EJP SOIL project. Adapted from: "Main European Regions" by Der Ständige Ausschuss für geographische Namen (StAGN) https://commons.wikimedia.org/wiki/File:Grossgliederung_Europas-en.svg [22.7.20] StAGN Webpage. South includes Southern European countries and Turkey.

1.2 Review of European projects and literature

The review of the projects took offset in the list of ongoing and completed EU FP7 and H2020 projects in Table 1 of EJP SOIL Annex 1 Description of the action Part B. Not all the listed projects were relevant for the respective subjects and thus excluded from the analysis. The literature review was primarily based on pan-European or global literature, as the review of national literature was done by the individual EJP partner countries, as detailed below. In many cases, the reviewed literature had been generated within the reviewed EU projects. Due to time constraints, we focussed strongly on recent (<10 yrs. old) pan-European publications.

1.3 Review based on national inputs

The national inputs were conducted in accordance with the guidelines described by Ruysschaert et al. (2020) and included interviews with members of the national hubs and a review of national literature (Appendix A). Based on national interviews with the scientific community and the literature reviews, the national teams reported back to Aarhus University in a web-based reporting system. These inputs were subsequently analysed by Aarhus University and BIOS Science/University of Natural Resources and Life Sciences Vienna (BOKU) with the main aim of identifying knowledge gaps for the EJP SOIL roadmap activities. Due to COVID19 restrictions, many countries were challenged in terms of establishing the national hubs and conducting interviews with representatives from the scientific community. The number of researchers interviewed were 254 in total and ranged between 3 and 26 for individual countries. Some researchers were interviewed for more than one topic. For the different subjects, the number of researchers interviewed varied between 142 and 187 and they represented universities (41%), national research institutes (47%) and non-governmental institutions (12%) (Table 1). The national contact persons played a key role in organising the interviews and reviewing the national literature. We acknowledge that biased views by these individuals may have affected the individual national reports. Such bias was, however, not expected to significantly influence the overall analysis and conclusions, as these were based on 24 national inputs and the review of European projects and literature.

Table 1. Number of researchers interviewed for the three specific topics within the EJP SOIL concept framework

Institution/sub categories	**Carbon stock**	**Soil degradation and fertility**	**Strategies for improved soil management**
University level	57	81	76
National institution	71	85	83
Non-governmental	18	21	23
Total	**146**	**187**	**182**

The number of documents retrieved and reviewed as part of the national literature reviews exceeded 1,800 with >420, >690 and >690 for 'Carbon stock', 'Soil degradation and fertility' and 'Strategies for improved soil management', respectively. The documents were mainly reviewed journal publications (72%) and reports (19%).

2 General results from the national inputs

As part of the national reporting, we asked the countries which Environmental zones were relevant to be considered for the specific country. Figure 5 shows a summary of these data. Continental was considered relevant for about 40% of the countries and Atlantic North, Atlantic Central and Alpine South for 25-30% of the countries. Anatolian (Turkey) and Alpine North (Norway) were only considered relevant by a single country. Boreal (Norway, Finland, Sweden), Nemoral (Lithuania, Latvia, Sweden), Mediterranean Mountains (Italy, France, Turkey) and Lusitanian (Spain, France, Portugal) were each relevant for three countries.

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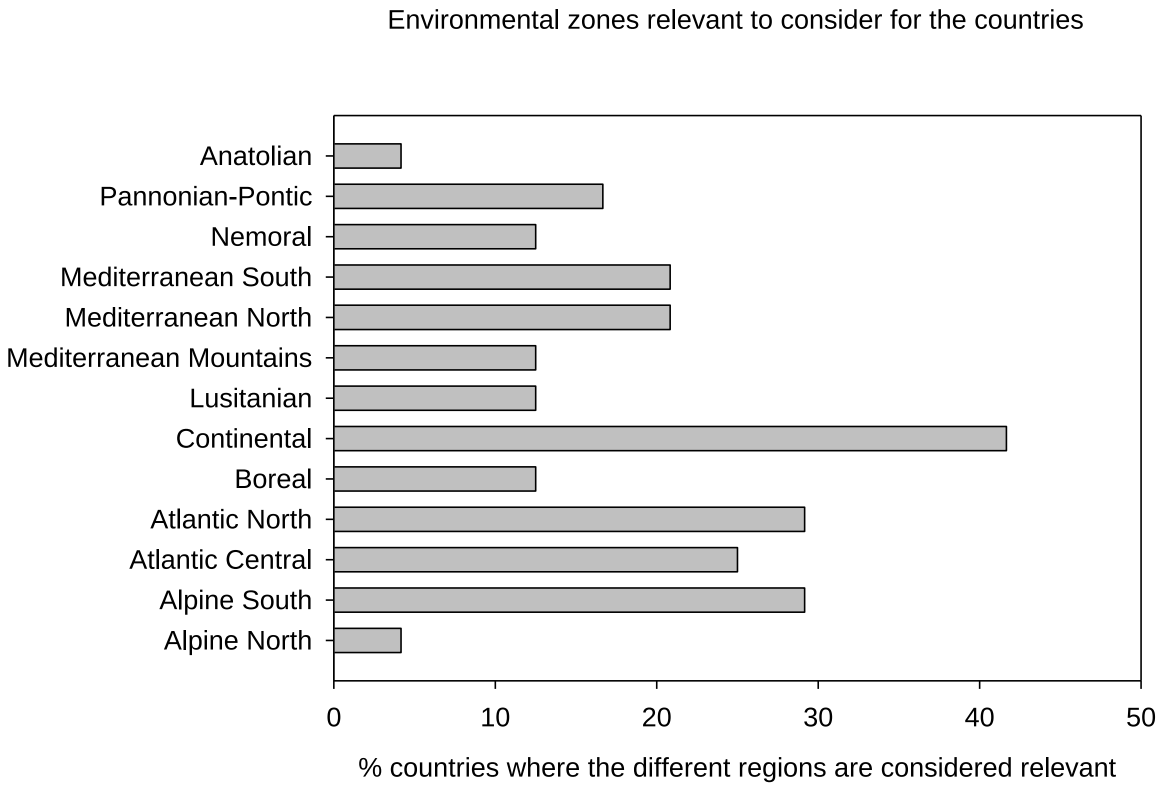

Figure 5. Relative number of countries (in %) where the different Environmental zones are considered relevant. The countries/regions included were France, Ireland, the United Kingdom, Belgium-Flanders, Belgium-Wallonia, the Netherlands, Denmark, Norway, Finland, Latvia, Lithuania, Sweden, Austria, Switzerland, the Czech Republic, Germany, Hungary, Poland, Slovakia, Slovenia, Spain, Italy, Turkey and Portugal.

We also asked the countries to answer the question 'What are the main soil challenges in the country?' A summary of the replies is shown in Figure 6. All countries considered 'Maintain/increase SOC' as a main challenge. 'Avoid soil erosion' was considered as a main challenge by 67-100% and 'Optimal soil structure' and 'Enhance nutrient retention/use efficiency' by 50-100% of the countries in all regions. 'Avoid salinization' was considered a main problem in all countries in the Southern region but not in any of the countries in Western and Central regions. 'Avoid peat degradation' was considered a challenge in 25-50% of the countries in all regions, although with the highest percentage for the Northern region.

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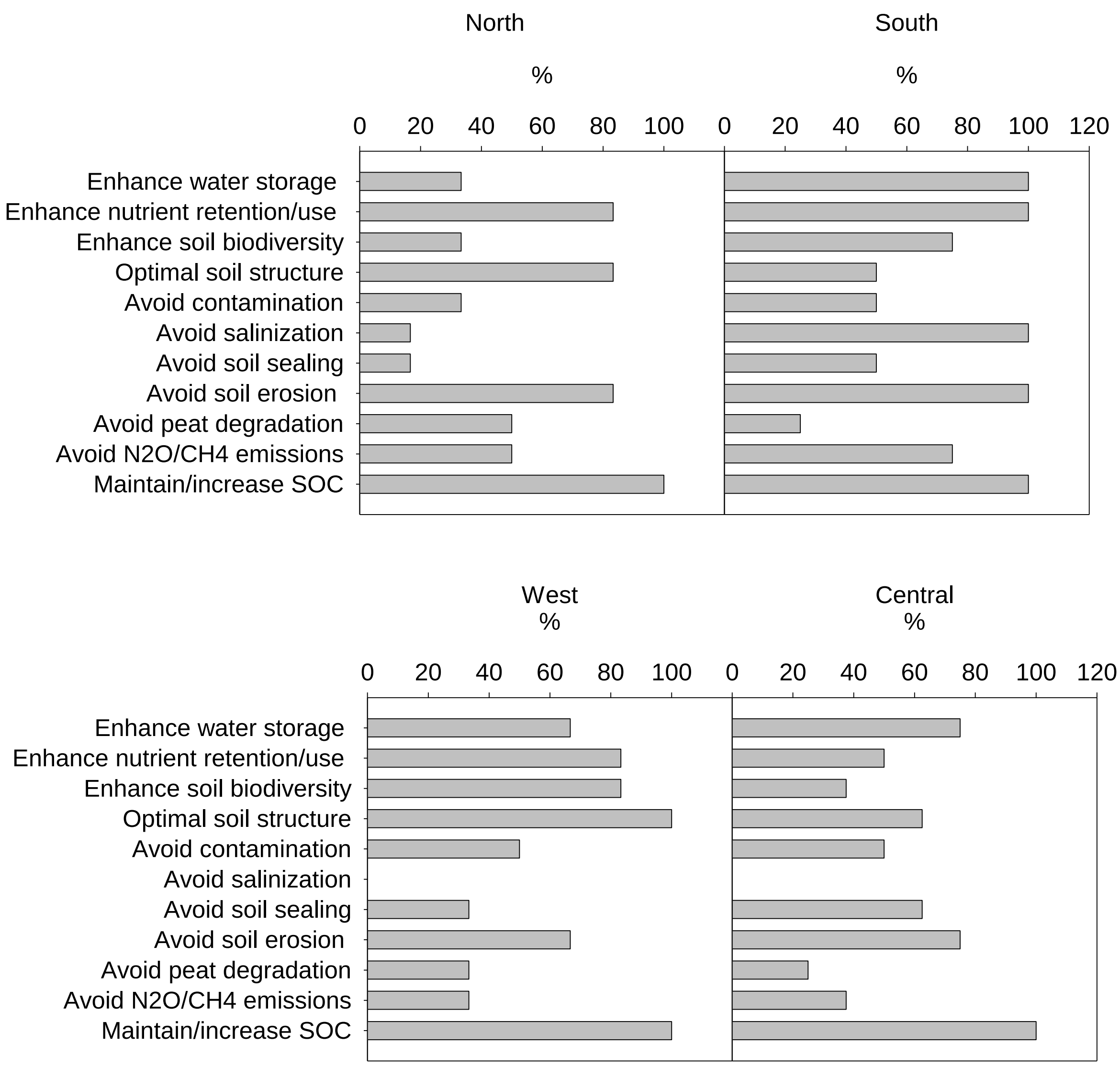

Figure 6. Main soil challenges within the country. Percentage replies for a specific challenge within a region. The Western region included Belgium-Flanders, Belgium-Wallonia, France, Ireland, the Netherlands and the United Kingdom; the Northern region included Denmark, Finland, Latvia, Lithuania, Norway and Sweden; the Central region included Austria, the Czech Republic, Germany, Hungary, Poland, Slovakia, Slovenia and Switzerland; the Southern region included Italy, Portugal, Spain and Turkey.

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3 Soil carbon stocks

3.1 Review of EU and international projects and literature

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3.1.1 Introduction

Soil is a key compartment for climate regulation since it both acts as a source of greenhouse gas (GHG) emissions and as a sink of carbon (C). Soil stores vast amounts of C, and the first meters of mineral soils contain between 1,500 and 2,400 Pg (Pg=1015 g) of organic C. That is approximately three times the stock of C in vegetation and twice the stock in the atmosphere (Smith et al., 2020). About 44% of this C pool is held in the top 0.3 m of the soil, the layer that is most prone to becoming altered by changes in soil use and management (Batjes, 1996). Peat soils and permafrost account for more than 1,500 Pg of C (Stockmann et al., 2013). Therefore, small changes in soil C stocks can have significant impacts on the atmosphere and climate change, and it has been suggested that soil C sequestration could be a significant GHG removal strategy (Lal et al., 2018).

Land use, land-use change and forestry is one of the five sources of GHGs included in the United Nations Framework Convention on Climate Change (UNFCC), affecting not only global GHG emissions but also biodiversity, and land and soil quality (UNFCCC, 1992). The loss of soil organic C (SOC) from agricultural land is identified as one of the eight major threats to soils, negatively influencing soil fertility and the soil's provision of ecosystem services (Schiefer et al., 2018).

There is growing international interest in improving soil management in order to increase SOC content, which will aid climate change mitigation, enhance resilience to climate change and underpin food security, through initiatives such as international '4p1000' and the Food and Agriculture Organization (FAO)'s Global assessment of SOC sequestration potential programme (see also Tables 1 and 1S). At the country level, accurate assessments of C stocks for a chosen baseline year, for example, '1990' as stipulated under the terms of the Kyoto Protocol (Smith, 2020), require extensive soil inventories, with associated information on recent land use history and management practices.

Cropland is the major land use in Europe, and changes in the size of the cropland soil C pool could significantly impact the European C budget (Janssens et al., 2005). Temperate grasslands account for c. 20% of the land area in Europe. Carbon accumulation in grassland ecosystems occurs mostly in the topsoil (0-25 cm) and changes in SOC stocks may result from land use changes (e.g., conversion of arable land to grassland) and grassland management (Soussana et al., 2004). Poeplau and Don (2013) carried out a study of 24 paired sites with different land uses in Europe comprising the major European land use change types, i.e., cropland to grassland and the reverse, cropland to forest and grassland to forest. They found that the SOC sequestration following the introduction of grassland in croplands equalled the SOC sequestration of afforestation on cropland. Converting grassland to forest had no significant effect on the total soil organic C stock. Lugato et al. (2014) used a modelling platform to estimate agricultural topsoil (0–30 cm) SOC stocks in continental Europe, and they showed that the agricultural SOC stock is 17.6 Pg on a pan-European scale. This is considerably less than the 75 Pg of SOC (0-30 cm) for all soils in the EU-27, where much of this is in the peatlands of Ireland, Finland, Sweden and the UK (EEA, 2015). Drained organic soils are significant net sources of GHG emissions such as carbon dioxide (CO_2). A recent supplement to the "2006 IPCC Guidelines for National Greenhouse Gas Inventories on Wetlands" (IPCC, 2014) proposed emission factors for temperate grassland on drained organic soil with low and high nutrient status, and cropland of between 5.3 and 7.9 Mg CO_2-C ha^{-1} yr^{-1} (Hiraishi et al., 2014).

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3.1.2 Methodology

Changes in SOC content cannot be easily measured due to the large background stocks, inherent spatial and temporal variability and slow soil C gains, which make the detection of short-term changes in SOC stocks challenging. A key barrier to implementing programmes to increase SOC at a large scale is the need for credible and reliable measurement, monitoring, reporting and verification platforms, both for national reporting and for emissions trading (Smith et al., 2020).

There are several soil C monitoring systems in Europe. However, soil monitoring networks are much denser in Northern and eastern European countries compared with countries located in the Southern part of the continent. For example, in France, the Soil Quality Monitoring Network was created 20 years ago for non-forested areas, covering the main land uses on a 16 km grid (King et al., 2005). In Denmark, soils are sampled approximately every 10 years to 1 m depth in a regular 7 km grid (Taghizadeh-Toosi et al., 2014). SOC monitoring in Belgium is based on a dataset of 13,000 soil profiles (Van Orshoven et al., 1988; Meersmans et al., 2011). In the UK, there are two national-scale soil monitoring networks across England and Wales (Bellamy et al., 2005; Reynolds et al., 2013). In Sweden, soil monitoring is performed at two geographical levels (national and regional) for arable lands (Olsson, 2005). Poland also has soil monitoring systems for cropland soils where soils have been sampled every eight years (Białousz et al., 2005). In several EU countries, including Italy, Spain and Greece, systematic national soil monitoring systems are not properly systemised or non-existent.

Models previously involved in simulating soil organic C storage in agricultural soils include ICBM, AMG, CANDY-CIPS, RothC and C-TOOL, with some of them being used for estimating SOC changes at regional and country levels (Taghizadeh-Toosi et al., 2020). The calibration step of models with long-term datasets is a critical point (Stockmann et al., 2013). Long-term field trials exist in various parts of the world, with some dating back to the 19th century. Results from these field experiments have been central for testing the accuracy of C models (Smith et al., 2020).

In addition, digital soil mapping has evolved as a discipline linking field, laboratory, and proximal soil observations with quantitative methods to infer spatial patterns of soils across various spatial and temporal scales (Smith et al., 2020).

3.1.3 Management effects on soil organic C

Management strategies such as conservation agriculture, improved residue management, mulch farming, cover cropping, inclusion of deep-rooted crops, agroforestry, biochar application, improved grazing and/or restoration of degraded soils, controlling erosion, and preserving peat soils were suggested for increasing SOC stocks (Dawson and Smith, 2007; Lal et al., 2018; Powlson et al., 2012). However, some studies suggest that a change of management practice cannot prevent ongoing losses of SOC from the topsoil (Steinmann et al., 2016).

3.1.4 Knowledge gaps

Despite decades of research, there is still an incomplete understanding of how SOC changes are influenced by climate, land use, management and edaphic factors (Stockmann et al., 2013). Particularly, process-level knowledge on how these factors influence changes in SOC stocks and fluxes remains incomplete (Bispo et al., 2017). Many approaches to quantify SOC stocks are based on data gathered over time and obtained with different methods for sampling and analysis. This makes results difficult to compare across the different countries or regions. In addition, the pedogenetic SOC inventories are ill aligned with the land use–based approaches (Wiesmeier et al., 2012). Furthermore, there is a scarcity of studies on other land categories such as mountains, bare ground, urban areas (including gardens) and lynchets. Likewise, more work on SOC stock estimates for peatlands is needed. This requires new methodologies to identify and access peat extent, status, peat thickness and its carbon content necessary for calculating current SOC stocks (FAO, 2020). A recent review by Minasny et al. (2019) demonstrated that digital soil mapping with nonlinear machine learning algorithms constitutes an avenue for mapping more accurately peatland areas. However, they emphasised also the lack of uncertainty assessment as a notable gap within current peat mapping studies.

Much of the efforts on studying SOC changes has been devoted to the topsoil. However, subsoils contain overall an even larger SOC stock than topsoils and may be affected differently from topsoil by land use, management and environmental change (Angst et al., 2018).

The reversibility of C sequestration, when practices that retain C are not maintained, or due to climate variability or climate change, increases uncertainty in the periods needed to monitor SOC enhancement activities. When assessing this net potential, special attention should be paid also to any possible adverse environmental effects, such as increases in other greenhouse gas emissions (e.g., nitrous oxide) associated with changes in SOC management. A socioeconomic module will be necessary to assess all potential costs and benefits associated with the various management options on SOC sequestration. There is also a lack of understanding of the real impact of policies, planning and regulations and of what makes a policy impetus effective or not for SOC sequestration, which needs to be addressed with a better understanding of the role of different administrative bodies in decision-making in setting up policies and planning.

Further information on the SOC sequestration potential and the mechanisms behind long-term soil C storage call for the use of advanced techniques, such as combining established databases, biomass partitioning, ecological surveys, land classification and remote sensing techniques (Smith et al., 2020). Several international and European initiatives/projects (see Project list below) have been addressing these issues and have identified a range of knowledge gaps (Table 2 and S1).

Acronyms of projects, initiatives and organisations of relevance for soil carbon storage

4 per 1000 - Soils for food security and climate

AGFORWARD - AGroFORestry that Will Advance Rural Development

CAPRESE - CArbon PREservation and SEquestration in agricultural soils

Catch-C - European FP7 project

CIRCASA - H2020 Coordination of International Research Cooperation in soil Carbon Sequestration in Agriculture

EIONET- European Environment and Observation Network

EIP-AGRI - The agricultural European Innovation Partnership

ESP - European Soil Partnership

FACCE-JPI - Joint Programming Initiative on Agriculture, Food Security and Climate Change

GCP - The Global Carbon Project

GRA - The Global Research Alliance on Agricultural Greenhouse Gases

GSBI - The Global Soil Biodiversity Initiative

GSOIL OCseq - Global assessment of SOIL organic C sequestration potential

GSP – The Global Soil Partnership for Food Security and Climate Change Adaptation and Mitigation

INSPIRATION - H2020 INtegrated Spatial PlannIng, land use and soil management Research AcTION

IPBES - Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

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IPCC - The Intergovernmental Panel on Climate Change

ISQUAPER – H2020 Interactive Soil Quality Assessment in Europe and China for Agricultural Productivity and Environmental Resilience

ITPS - Intergovernmental Technical Panel on Soils

JRC – The Joint Research Center

Landmark - European Research Project on the sustainable management of land and soil in Europe

LANDSUPPORT - Development of Integrated Web-Based Land Decision Support System Aiming Towards the Implementation of Policies for Agriculture and Environment

RECARE - Preventing and Remediating degradation of soils in Europe through Land Care

SMARTSOIL - Sustainable farm Management Aimed at Reducing Threats to SOILs under climate change

SoilCare – SoilCare for profitable and sustainable crop production in Europe

UNCCD - The United Nations Convention to Combat Desertification

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Table 2. Projects, initiatives and organisations organised according to the topic of their focus with the most important knowledge gaps in relation to SOC stocks.

Topic	Knowledge gap	Project or initiative
Climate	• Projected response of C stock to climate change • Possible adverse environmental effects, such as increase in other GHGs with C-promoting management • Lack of carbon-climate-humans system interactions and how this system can be managed by societies	4 per 1000, ITPS, GCP
Land use	• Effects of C sequestration on crop and grassland yields and ecosystems • Assessments of land use change and fire effects on SOC • Include more land categories (such as: mountains, bare ground, urban areas, and lynchets)	4 per 1000, IPBES
Management	• Assessment, projection and mapping under various management and in relation to the future climate change scenarios • How good practices vary in different geographical, social and soil/climate conditions • Expanding life cycles of practices and farm inputs beyond farm scale • Understanding of grazing management practices that sequester C in specific regions • Machine learning and biogeochemical modelling to investigate effects of climate and management interactions on C cycling • Socio-economic module to assess potential costs and benefits of various management options on SOC sequestration	4 per 1000, JRC, Catch-C, CIRCASA, EIP-AGRI, "Grazing for carbon"
Edaphic Factors	• Relevance of pedogenetic SOC inventories instead of land use-based approaches • Estimations of SOC stocks in subsoil • Knowledge on biophysical and biochemical interactions with SOC • More explicit representation of small-scale microbial controls • New controls for interactions among organisms and abiotic environment in the context of wetland restoration • Effects of soil erosion in the global C cycle, specifically wind soil erosion	ITPS, GSP, 4 per 1000, IPBES, ESP
Quantification	• Harmonization of existing methods for SOC stocks sampling and analysis • Novel techniques for obtaining information on C storage potential and mechanisms behind long-term C storage, including spectral methods, proximal and remote sensing, spatially-explicit mapping, combination of established databases, 'Big data' analysis, machine learning, use of biomass partitioning, ecological surveys and land classification • Considering organic matter types including particulate organic and mineral-associated organic matter	UNCCD, IPCC, ESP, GSP, GRA, EIP-AGRI, JRC, LANDMARK, Agroforward, GSBI, SoilCare
Monitoring	• Need for uncertainty assessment of long term experiments • Assessments of historic loss and future trends in soil organic C pools, their characteristics and properties	GRA, CIRCASA, GSP, Landmark, ESP, ITPS
Scale	• Importance of SOC and its spatially-resolved representation on regional and global scales • Inconsistent information of SOC spatial and temporal dynamics	ITPS, GSP, ESP, INSPIRATION

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Farmers	• Lack of factual support, credible low-cost tools for farmers to improve soil management for enhanced C sequestration • Need to consider both farm and farmer heterogeneity in the studies • Use of C sequestration and climate regulation models for farmers and advisors	ISQUAPER, Landsupport, SmartSoil
Policy	• Lack of understanding of the impact of policies, planning and regulations on C sequestration • How to use modelling results towards C-neutral food systems based on the policy needs • Lack of sufficient information for large stakeholders to effectively manage C emissions	GCP, INSPIRATION, FACCE-JPI, Climate-KIC

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3.2 Synthesis of national inputs

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The carbon (C) stock synthesis is focusing on the knowledge gaps expressed by the member states of the EJP SOIL. Relevant state-of-the-art knowledge, stated by the countries, is presented in this section as well. This section is structured according to the four main European regions defined within this programme (Figure 4). Knowledge gaps were categorised into five topics, which are presented in detail for each region:

- Knowledge gaps regarding soil management for carbon
- Knowledge gaps regarding assessment and monitoring of soil carbon
- Knowledge gaps on modelling
- Knowledge gaps from a farm and soil policy perspective
- Knowledge gaps on organic soils

3.2.1 Northern region

The following synthesis is based on NO, DK, FI, LV, SE and LT inputs. EE did not provide contributions for this report. LV submitted data on state-of-the-art knowledge on carbon stocks, but no contribution regarding knowledge gaps.

3.2.1.1 Knowledge gaps regarding soil management for carbon

Within the Northern region, NO stated that the information on SOC stocks in their country is limited. Further, they reported a lack of documentation on the effects of management practices such as crop residues retention, biochar application and cover/catch crop establishment on SOC. There is an urgent need to gain more knowledge on the effects of different crop production systems on SOC stocks. SE states that there are many meta-analyses and reviews on SOC change factors, but the great variations between different study sites remain largely unexplained.

DK stated that management effects on SOC storage in deeper soil layers are understudied. Knowledge on C input in the subsoil by roots of different crops and ways to modify them in SOC simulation research is needed. Further, DK pointed out the need for addressing knowledge gaps on the threshold levels of crop residue removal without jeopardizing soil quality. Moreover, the information provided by farmers is often not detailed enough to isolate the specific effects of different combinations of management practices used for crop cultivation. A differentiated view of management options is therefore often not possible. As in DK, knowledge on deep soil carbon dynamics is missing in FI and SE.

LT identified a need for research on organic amendments for increasing SOC stocks. Currently, the country is concerned about the possibilities of improving the soil C sequestration rate, as most studies suggested that SOC stocks in mineral soils in this region cannot be improved significantly by changing agricultural management practices.

3.2.1.2 Knowledge gaps regarding assessment and monitoring of soil carbon

NO highlighted the need to agree on a common way to monitor SOC stocks and storage potentials nationally and internationally. They further stated the amount of SOC in Norwegian agricultural soils needs to be assessed and feasible threshold values should be discussed. For example, it was emphasised that some soils have a loss of ignition value above 20, whereas other state factors

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between 3 and 4. These soils vary greatly in their C dynamics and it has to be recognised that high-value soils may offer limited C storage potential.

A nationwide 7 km grid on arable land, which is used for the Danish inventory data collection on SOC stocks, is sampled every 10 years (1986, 1997, 2009, and 2017). The inventory from 1986-2009 showed that the average SOC distribution was 63, 41, and 38 t C ha^{-1} in the 0–25, 25–50 and 50–100 cm depths, respectively. DK identified a need for research on accounting for historic land use and SOC distribution in their country.

A lack of knowledge on SOC monitoring and investigations in qualitative C parameters was expressed by LT.

FI states research needs on physical, chemical and microbiological processes affecting SOC. Further, the different carbon fractions relevant to stable carbon storage are understudied. Long-term monitoring and new methods are important to obtain accurate data on management practice impacts on SOC under different conditions.

3.2.1.3 Knowledge gaps on modelling

FI stated that models for scenario analysis are needed in their country. Carbon balance modelling studies are ongoing but need improvement. LV uses the Yasso07 model to estimate SOC changes in agricultural land. Yasso07 results show an underestimation of carbon stocks when comparing the results with measurements within the 'Biosoil2012' soil survey. These inconsistencies may be explained by inappropriate non-woody biomass input data. SE found low agreements between SOC change estimates from national soil inventories and models using the Tier III approach. These differences indicate knowledge gaps concerning SOC dynamics, which are probably related to belowground C inputs and pedoclimatically dependent stabilization mechanisms. Results of recent studies indicate that the Tier II model, which is also used in the Swedish Inventory Report (NIR), overestimated emissions from drained peat soils. Therefore, more empirical studies on different types of organic soils are needed as a basis for the model.

3.2.1.4 Knowledge gaps from a farm and soil policy perspective

LT highlighted that knowledge on monitoring C and other soil properties would aid stakeholders in making the right decisions regarding sustainable soil management.

3.2.1.5 Knowledge gaps on organic soils

Danish wetlands under agriculture were reduced by 35% between 1975 and 2010, caused by drainage and tillage. DK identified several knowledge gaps concerning organic soils, above all regarding possibilities for protecting organic soils by rewetting. Further, updated maps of peatland, groundwater levels and C stocks in organic soils are still missing. Quantification of C loss rates in peat soil is needed as well. There is no national monitoring of GHG emissions, but the identification of controlling factors in representative areas is in progress.

FI stated a major share of GHG emissions comes from agriculturally managed peat soils in their country. They reported that the impacts of groundwater levels are known, but measures to reduce GHGs where water levels cannot be raised are needed.

3.2.1.6 Summary

In summary, the main knowledge gaps identified within the Northern region are (in no specific order of importance):

- Effects of management practices such as residues retention, biochar application and cover/catch crop establishment on SOC
- Management effects on SOC storage in deeper soil layers

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- Carbon input in the subsoil by roots of different crops and ways to modify them in SOC simulation research
- Threshold levels of crop residue removal without jeopardizing soil quality
- Specific effects of different combinations of management practices
- Physical, chemical and microbiological processes affecting SOC in different carbon fractions
- Harmonised methods to monitor SOC stocks and storage potentials nationally and internationally
- Models for scenario analysis
- Accounting for historic land use and SOC distribution
- Investigations of qualitative C parameters
- Protection of organic soils by rewetting
- Updated maps of peatland, groundwater levels and C stocks in organic soils
- Quantification of C loss rates in peat soil
- National monitoring of GHG emission of peat soils

3.2.2 Southern region

The following synthesis is based on PT, IT, ES and TR inputs. IT focussed on the knowledge available within the country, and no report on knowledge gaps was provided.

3.2.2.1 Knowledge gaps regarding soil management for carbon

PT requires studies on the effects of roots and biochar on SOC stocks. The application of biochar and the effects on SOC sequestration are also understudied under Turkish conditions. Long-term studies on the Montado systems, which are Portuguese agro-silvopastoral systems with cork or holm oak, are required to evaluate their effects on soil processes and climate change. A previous study conducted on a Montado system found that SOC concentrations were higher under the tree canopy compared to the part of pasture without tree cover. IT concluded that the adoption of annual alley crops, minimum tillage and organic fertilization led to the best results regarding SOC sequestration in woody crop plantations. Moreover, intensive systems growing arable crops are dominating IT's agriculture. Unfortunately, the intensification and simplification of crop rotations led to several environmental issues, such as SOC depletion. When targeting SOC sequestration measures, the regional pedoclimatic differences throughout the country should always be considered.

Although there are already many studies on SOC contents for Turkish agricultural land, there is still insufficient knowledge on C sequestration and GHG emissions under different agricultural management practices. In many cases, studies on this topic are conducted on a local scale, and therefore an upscaled approach is missing. Specifically, SOC stock potentials need to be investigated for several management options. Projects dealing with the effects of tillage systems and organic materials on SOC sequestration are currently running. Further, there is a lack of knowledge on soil respiration and the C budget of soils in different agricultural systems of TR.

ES reported research needs regarding C sequestration affected by management in grassland soils and long-term studies on a broader range of representative systems, as C storage potential appears to be affected by the duration of the use of the Recommended Management Practices. Alongside, knowledge on the effects of different management on SOC and its fractions is needed for all types of agrosystems. Studies, stated within the Spanish report, suggest that there is a great potential for improving or restoring SOC in Spanish Mediterranean croplands through Recommended Management Practices.

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3.2.2.2 Knowledge gaps regarding assessment and monitoring of soil carbon

PT stated that their SOC monitoring is mostly limited to topsoils (0-15 or 0-20 cm depth), which leaves the contribution of subsoil organic C on soil functions largely unknown. Throughout the ENVASSO survey, it was found that bulk density was measured in PT only at 10% of the monitoring sites, which shows the urge to increase bulk density measurements in the future. A national study monitoring SOC in the topsoil of an improved pasture successfully used geospatial Normalized Difference Vegetation Index measurements, showing the potential of this technique to generate SOC maps.

TR stated their national priority is to increase SOC contents, since only 14% of soils have a SOC content of more than 2%, whereas 64% of soils have less than 1%. An important step was “The National Geospatial Soil Fertility and Soil Organic Carbon Information System Project”, which focussed on establishing a topsoil organic C geospatial database using representative soil samples. The first SOC stock map was presented in 2015 and was updated with over 22,000 soil samples in 2019.

Knowledge gaps in accounting for the coarse soil fraction, bulk density and soil mass when determining carbon stocks were found by ES. When quantifying C storage, not only C sequestration but also C outputs should be acknowledged. ES identified a lack of integrated field experiments in a broader range of representative systems in the Mediterranean region to monitor the long-term effectiveness of management strategies on SOC changes and GHG emissions, in particular in association with irrigation and fertilization. A historical perspective (1900-2008) on the evolution of SOC in ES’s cropland is available.

3.2.2.3 Knowledge gaps on modelling

To improve Portuguese SOC turnover models, more knowledge on the quality of SOC is necessary. Moreover, only a few studies on the prediction and modelling of SOC storage potentials were identified for PT.

Studying SOC sequestration and dynamics in the field is time-consuming and costly. Therefore, IT emphasised the use of models (e.g., Century, EPIC, RothC, RothC10N) to estimate those processes.

3.2.2.4 Knowledge gaps from a farm and soil policy perspective

As mentioned above, knowledge on SOC quality is not only vital as an input for organic matter turnover models, but also to advise Portuguese policymakers on the mitigation potentials of several soil management practices.

3.2.2.5 Knowledge gaps on organic soils

For this region, no knowledge gaps regarding organic soils were stated.

3.2.2.6 Summary

In summary, the main knowledge gaps identified within the Southern region are (in no specific order of importance):

- Effects of roots and biochar on SOC stocks
- Long-term studies on the silvopastoral Montado and Dehesa (identical systems with different names in PT and ES) systems
- Effects of different management on SOC fractions
- Carbon sequestration and GHG emissions under different agricultural management practices
- Soil respiration and the C budget of soils in different agricultural systems
- SOC monitoring of deeper soil layers
- Bulk density measurements
- More knowledge on the quality of SOC
- Modelling SOC storage potentials

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- Monitoring of SOC changes and GHG emissions in long-term field experiments in the Mediterranean region

3.2.3 Central region

The following synthesis is based on AT, CH, CZ, DE, SK, SI, PL and HU inputs.

3.2.3.1 Knowledge gaps regarding soil management for carbon

AT pointed out that the understanding of SOC formation pathways and pool-specific saturation deficits in conventional farming systems opposed to innovative systems and cover cropping are significant knowledge gaps. Further, root-derived C might significantly contribute to stable SOC stocks. Unfortunately, most experiments researching these mechanisms are conducted in artificial systems, which lack ecological relevance. AT moreover stated the need for knowledge on modern management options that enhance SOC sequestration and storage, as farmers continuously develop new practices.

SI stated that the favourable effects of biochar, such as increasing water and air quality and nutrient leaching prevention, were investigated thoroughly.

The CZ highlighted that research on organic wastes and their safe use as amendments deserve close attention. They further expressed that strengthening soil buffering mechanisms and focusing on precision agriculture and advanced technologies in large-scale farming are important.

DE also addressed the need for studies on the impact of alternative composting technologies (e.g., digestates from biogas production or biochar) on soil functions and the environment (e.g, GHG emissions or harmful substances).

Due to CH’s large area with integrated grassland and application of integrated and organic cropping, it is estimated that the sequestration potential for arable land is limited.

PL stated that there are important gaps regarding subsoil SOC and SOC analysis, as so far, there had been no demand for this information.

3.2.3.2 Knowledge gaps regarding assessment and monitoring of soil carbon

Within the Central region, AT does not have a monitoring system for organic C in mineral agricultural soils but conducted a SOC content and stocks estimation within the project ASOC (Austrian map of SOC). Carbon sequestration potentials are going to be evaluated in the ongoing CASAS (CArbon Sequestration in Austrian Soils) project. Further, research on the different C pools, their vulnerability to decomposition and duration of C storage is needed according to AT. A standardization of SOC analysis is crucial to identify those pools. Alongside, factors affecting the spatial variation of SOC stocks are seen as a knowledge gap. Modern remote sensing approaches in combination with machine learning algorithms are promising but need to be validated with SOC analyses data at various scales.

CH highlighted the lack of available soil information at a sufficient temporal and spatial resolution, which is the major limitation to related estimations and modelling. More specifically, data on land-use, clay content, subsoil skeleton content, subsoil C stocks and the hydrological state of soils is often missing. Further research gaps are organic C dynamics in deep soil layers, historical and recent C inputs in top- and subsoil and the impact of the hydrological status on SOC. Knowledge of SOC stocks in Swiss soils largely originates from long-term field experiments and soil monitoring networks.

The CZ started a monitoring network in 1992 consisting of 190 sampling sites, which are sampled every six years to assess basic soil properties. Arable soils are sampled down to 60 cm depth, grassland soils down to 40 cm depth. Alongside, they apply models and remote sensing technologies, like Visible- and near-infrared diffuse reflectance spectroscopy, to reduce the need for expensive sampling.

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Similarly, PL has been monitoring their C trends in arable soils since 1995 in five-year intervals. There are 216 permanent sampling locations spread across the country and the data is publicly available. A large SOC content database from the 1990s provides information from approximately 50.000 sampling locations, which equals on average one sample per 400 ha of agricultural land, and therefore describes PL's spatial variability well. Further data was collected between 2016 and 2017 in the process of the CAP impact evaluation programme. A lack of accessibility to the results of PL's long term experiments was identified. Further, major gaps in the monitoring of grasslands were stated.

The national monitoring in HU is done by the Soil Protection Information and Monitoring (TIM) system, which has been sampling 1236 points every three years since 1992.

The Slovakian Soil Monitoring System was created in 1993 and is assessing SOC concentrations every five years down to 45 cm soil depth.

SI stated that C sequestration is not sufficiently investigated in their country.

DE reported knowledge gaps on the C sequestration potential of their soils too, and how the sequestered C is reversible and affected by future climate change scenarios. According to DE, the largest knowledge gaps concern the quantification of C inputs by crops, in particular by roots and rhizodeposition, and the assessment of the quality of such C inputs. Research needs regarding this topic have been stated by several other countries before. The role of microorganisms and exoenzymes concerning SOC stabilization is considered important as well. Lastly, improved monitoring of SOC stocks is needed, in particular monitoring of the agricultural practices by farmers and the driving factors for the management.

3.2.3.3 Knowledge gaps on modelling

Several results from SOC modelling in AT's agricultural soils are available. However, more long-term datasets are essential to assess how long predictions can be extended without incorporating the long-term stabilised soil organic matter (SOM) pool into the model calculations.

HU highlighted their national SOC maps and models. Modelling of SOC is done by several research groups, mostly focusing on a local scale.

The RothC model was used to calculate the SOC stocks and changes in the mineral and organic soils of CH between 1990 and 2018.

SK stated that their SOC model is lacking precise input data and therefore shows limitations, as only general and inaccurate estimations can be made. The results from modelling at farm-scale have only restricted information value. National coverage with sufficient local detail is needed. CH similarly stated a need for soil information at a sufficient spatial and temporal level.

PL did not report knowledge gaps regarding modelling.

3.2.3.4 Knowledge gaps from a farm and soil policy perspective

CH developed a decision support tool for farmers to assess the SOC stock changes based on input and SOC decomposition.

A lack of information exchange between research and farmers of the CZ was claimed. Similarly, SI expressed gaps in the transfer of knowledge from research into practices and legislation. Legislation in SI does not aim at all essential goals, which are necessary to achieve improved soil management.

DE expressed a lack of communication from a scientific perspective to other stakeholders.

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Throughout the CAP monitoring programme in PL, SOC measurements on 600 farms were conducted to measure the effects of various CAP instruments. By surveying soil management and crop production, linkage of SOC status to agricultural practices and policy instruments was enabled.

3.2.3.5 Knowledge gaps on organic soils

As for mineral soils, there is no monitoring of C stocks for organic soils in AT. The available data on SOC in peatland needs to be improved, C stocks should be measured to at least 50 cm depth and the size and dynamics of the C pool need to be studied.

DE expressed a need for research on how rewetted peat soils can be cultivated without increasing their GHG emissions.

PL recently started an initiative that is monitoring agricultural organic soils. Two-thousand sampling locations, based on the national agricultural map, can be compared with the initial SOC values from the 1960s and '70s. The first results show a drastic decrease in SOC in drained or converted agricultural soils and grasslands.

3.2.3.6 Summary

In summary, the main knowledge gaps identified within the Central region are (in no specific order of importance):

- Understanding of SOC formation pathways and pool-specific saturation deficits in conventional farming as opposed to innovative systems
- Contribution of root-derived C to (stable) SOC stocks and C quality
- Organic C dynamics in deep soil layers
- Research on organic wastes, composting technologies and safe use as soil amendments
- Standardization of SOC analysis
- Insufficient monitoring of mineral and organic soils
- Lack of available soil information at a sufficient temporal and spatial resolution → major limitations to related estimations and modelling
- Achievable C sequestration potential
- Transfer of knowledge from research into practice and legislation (see report 2.2)
- Research on how rewetted peat soils can be cultivated without increasing GHG emissions
- Research on the different C pools and their vulnerability to decomposition and duration of C storage
- The role of microorganisms and exoenzymes in SOC stabilization
- Historical and recent C inputs in top- and subsoil
- Lack of accessibility to results of long term experiments

3.2.4 Western region

The following synthesis is based on the inputs by FR, IE, UK, BE-VLG, BE-WAL and NL.

3.2.4.1 Knowledge gaps regarding soil management for carbon

Mostly, when carbon (C) sequestering agricultural measures are identified, their fundamental processes can be narrowed down to an increased production of biomass or an enhanced return of C to the soil. FR stated that increased C stocks in soils can mitigate climate change, but that the valorisation of biomass for renewable energy production could be an alternative. Thus, there is an urgent need for addressing the comparative interest of different ways of exploiting biomass. French research rarely includes the factor "time" as a variable in the evaluation of changes in practice. Such

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research should be done for each relevant management practice for several years to assess long-term trends.

Evidence from soil surveys and long-term experiments in the UK suggests that knowledge gaps remain about the interactive effects that different management practices may have on soil SOC stocks and soil SOC stock change over time. For example, nutrient fertilization is usually associated with increases in SOC stocks in grasslands, but interactive effects between nutrient fertilization, grazing, the application of agricultural lime and farming traffic (which can increase soil compaction) need to be further addressed. Nor is the overall effect of arable cropping systems and associated management practices on net soil C gains and losses clear, especially under climate change.

Studies from BE-VLG concluded that non-inversion tillage is leading to a redistribution of C throughout the soil profile, but an increase of the stock could not be proven. Further, there is a need to quantify the effects of land-use change, land-use types and management options on SOC stocks. Moreover, BE-VLG reported research needs concerning regionally differentiated studies on management practices that effectively increase SOC contents, especially regarding grassland. Above all, the combined effect of measures on SOC needs to be investigated.

BE-WAL reported knowledge gaps on intercropping in terms of unwanted GHG emissions, carry-over effects on the subsequent crops and ecosystem services. BE-WAL highlighted the potentials of deep roots, subsoil C sequestration and storage. Further, biochar, its risks and potentials and the best conditions for application should be addressed. BE-WAL moreover suggested a life cycle analysis of contrasting agricultural systems to evaluate their overall performances on SOC sequestration and GHG emission. Lastly, studies on the use of organic wastes and their consequences for soil C turnover processes in agriculture deserve close attention.

The Netherlands is currently running the program ‘Slim Landgebruik’, which is tackling several national knowledge gaps. Along with other goals, emission factors for agricultural measures are registered and a realistic estimate of land on which measures can be applied is assessed within the program. Moreover, the effects of synergies and trade-offs of combined measures on SOC sequestration are investigated, which was also stated as a research need in BE-VLG.

3.2.4.2 Knowledge gaps regarding assessment and monitoring of soil carbon

Soil organic C research mainly focuses on topsoil, although it is well known that the residence time of SOC is often higher in deeper soil layers. FR expressed a lack of knowledge on the fate of deep soil C and its vulnerability. Moreover, the combined effects of land-use history and change, pedoclimatic factors and soil management practices on the spatial distribution of C stocks is understudied. The effects of urbanization on SOC stocks should also be addressed in future studies. FR reported advances in the specification of methodologies, as an International Organization for Standardization (ISO) standard for estimating SOC stocks is currently being established. Nevertheless, a standardised, international method for soil C stock assessment that is reliable and easy to apply is still missing. In particular, international harmonisation of methods for soil sampling and C analysis methods, sampling depths, bulk density assessment of samples and whether to use a grid at random or rational sampling is needed.

BE-VLG speculated whether information of the physical fractionation can help predict the decomposition of native SOC and, similarly to FR, whether an easy-to-use method to analyse SOC stability could be developed. Moreover, recent data on SOC stocks are needed, therefore a monitoring network will be rolled out in the coming years.

BE-WAL reported a lack in the monitoring of agricultural C stocks. A monitoring network already exists but needs to be improved.

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The Netherlands has recently monitored their C stocks (2013-2020) and will compare them with the data from 2005-2009. SOM data is available for the period 1998-2018.

IE expressed a national lack of knowledge on SOC processes operating at a biosphere to biome scale. At the landscape scale, agricultural management modifies large- and small-scale processes greatly, which themselves interact strongly. Therefore, IE highlights that a framework that can be integrated across a continuum of scales to optimise SOC management and more knowledge are required in this area. Further, research is needed to gain a deeper understanding of long-term SOC storage mechanisms and the potential to sequester C. Similar to FR, IE stated that most inventories and models only consider the top 30 cm of soil, but to properly assess SOC stocks, deeper soil layers (0-50 cm) should be sampled and/or modelled as well. Further, there is no monitoring system to assess changes in SOC stocks for IE. The establishment of a remote sensing approach is restricted due to the heavy cloud cover over the country and because only SOC concentrations can be measured and not the C stock, as bulk density is not assessed with this approach.

In the UK GHG Inventory, broad estimates of achievable C sequestration in mineral soils are available. An average soil C sequestration potential of approximately 2822 kt C in the next 30 years is estimated, a significant proportion of which is stored by grasslands not subject to land-use change. Evidence from long-term experiments established at Rothamsted (England) suggests that soils may reach a new C saturation equilibrium around 100 years after a land-use change. Finally, cropland in the UK is considered a net source of C emissions (3842 kt C by 2050).

3.2.4.3 Knowledge gaps on modelling

Soil organic C sequestration simulations in FR need to consider several climate change scenarios, and mitigation levers need to be considered in the context of agriculture that would have adapted to the changing climate. A French study synthesised knowledge on SOC modelling and predicted C storage potentials. Moreover, the achievable C sequestration of agricultural soils was estimated for FR.

BE-VLG highlighted the SoilGen model, which is an integrated model that incorporates the C cycle of mineral soils and feedback mechanisms between SOC, soil properties and agricultural management.

In BE-WAL, a regional map of stable C sequestration potential was produced, which gives information on the agricultural land that can contribute most to C sequestration in the future.

Current modelling and monitoring approaches are not adequately quantifying land use and soil management effects on SOC stock changes in the Netherlands.

In the UK, modelling studies suggest losses of SOC from arable land and gains in SOC in grassland following changes in land use. Challenges remain in the quantification of C inputs to soils as a key parameter that can affect model outputs as well as the effect of waterlogging or different management practices.

3.2.4.4 Knowledge gaps from a farm and soil policy perspective

FR stated that there is a need for simple sampling techniques to assess soil C stocks at farm level. This would allow farmers to evaluate the conditions of their soils more frequently. Further, the most efficient national policies and incentives, aiming to improve SOC stock should be identified for FR, and payments for C storage remain to be established.

BE-VLG highlighted that more knowledge on stimuli, enabling SOC increase on a farm scale, is needed. These stimuli could be financial or educational, besides others. An accurate and cost-effective system for accounting for C and quantifying the benefits of enhanced SOC is essential to motivate farmers.

BE-WAL suggested the simulation of potential SOC gains by pioneer agricultural management options to support decision-makers in determining climate change mitigation measures.

3.2.4.5 Knowledge gaps on organic soils

In IE, the mild maritime climate favours the formation of peat soils, which make up approximately 20 % of Irish soils. A more accurate estimation of drained land regarding extent and state is required. This could help to assess the distribution of drained organic soils or peatlands, which are losing C. Remote sensing tools can only support identification but give no information on temporal aspects of implementation or the degree, current status and effect on organic soils.

3.2.4.6 Summary

In summary, the main knowledge gaps identified within the Western region are (in no specific order of importance):

- Different ways of exploiting biomass (bio economy/biofuels vs. return to soil) and their climate mitigation potential
- Biochar, its risks and potentials
- Organic wastes and processes to make them safe for use in agriculture
- Life cycle analysis of contrasting agricultural systems to evaluate their overall performances in terms of SOC sequestration and GHG emission
- Potentials of deep roots and subsequent subsoil C sequestration and vulnerability
- Combined effects of environment and land use on SOC spatial distribution
- Combined effect of management practices on SOC
- A standardised, international, easy-to-use method for soil C stock assessment
- SOC processes operating at a biosphere to biome scale
- Lack of monitoring/insufficient monitoring of mineral soils
- Simple SOC sampling techniques for farmers
- Identification of the most efficient national policies aiming to increase SOC stocks
- Accurate estimation of degraded peatland

3.2.5 General analysis across regions

This chapter provides a general analysis across the four regions. The focus is on the main knowledge gaps summarised for each region. Some national inputs focussed more on the state-of-the-art knowledge, whereas others pinpointed the most important knowledge gaps. It needs to be acknowledged that the information is biased by the expertise of the individual persons providing the national inputs. Overall, valuable information was compiled. Most importantly, several similar knowledge gaps were highlighted by member states in all regions.

Firstly, all four regions expressed an urgent need for research on **deep soil carbon** and its dynamics. In particular, knowledge on deep SOC stocks, their vulnerability, sequestration potentials and the effects of management is sparse and monitoring programmes are missing. Further, the impact of **deep roots** on C stocks, their contribution to SOC sequestration and ways to effectively include them in SOC simulation research were highlighted as critical knowledge gaps. The Central region stated the need for research on different C pools, their vulnerability to decomposition, the duration of C storage as well as the historical and recent C inputs both in top- and subsoil.

Concerning the management of agricultural soils, the Southern region stated knowledge gaps on C sequestration and GHG emissions under different agricultural management practices. Further, there is a lack of knowledge on the effects of different agricultural systems on soil respiration and the C budget of soils. The effects of management practices such as residue retention and cover/catch crop establishment on SOC are understudied in the Northern region. Biochar and its risks and potentials for increasing long-term SOC stocks are insufficiently studied in the Southern, Northern and Western

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regions. The Central and Western regions mentioned the need for studying the potential of organic wastes and the processes for how to increase their safe application in agriculture. The combined effect of various simultaneous measures on SOC is stated as a knowledge gap in the Western region. Lastly, threshold levels of crop residue removal without jeopardizing soil quality and the different ways of exploiting biomass deserve close attention in the Northern and Western region, respectively.

In regard to monitoring SOC, many countries from the Central, Southern, Western and Northern regions reported insufficient monitoring and a need for a common monitoring system on national and international bases. DK presented its advanced inventory on SOC stocks, which is sampled every 10 years. AT stated that modern remote-sensing approaches, combined with machine learning algorithms, are promising but need to be validated with SOC analyses data at various scales. The CZ highlighted their monitoring networks for SOC. Alongside, they apply models and remote-sensing technologies such as Visible and near-infrared diffuse reflectance spectroscopy to reduce the need for expensive sampling. HU, PL and SK conduct SOC monitoring as well. DE expressed the need to monitor the socio-economic drivers for specific soil management practices in order to be able to analyse how and why SOC maintenance or improvements are done by farmers – is it really only a question of money?

As stated by CH, a major limitation to estimating and modelling SOC is the lack of information on SOC stocks and dynamics at a sufficient temporal and spatial resolution. In the Southern region, a lack of modelling SOC storage potentials was stated. The need for improving SOC modelling approaches was also stated by the Central, Northern and Western regions. In this regard, FR reported that an ISO standard for estimating SOC stocks is currently being established. Further, a French study synthesised knowledge on SOC modelling and predicted C storage potentials. HU highlighted their national SOC maps and models. SE expressed the need for more studies on peat soils as a basis for GHG emission modelling. The Northern region also highlighted that accounting for historic land use is of importance. Further, the Western region reported a lack of knowledge on the spatial distribution of SOC and SOC processes operating at a biosphere- to biome-scale.

The Western and Central regions emphasised that a standardised, international, easy-to-use **method for soil C stock assessment** is essential for future SOC research. The Southern region claimed that soil bulk density is often not assessed during sampling, which results in imprecise calculations of SOC stocks. More knowledge on the quality of SOC should be generated and investigations of qualitative C parameters conducted, according to the Northern and Southern regions, respectively. The understanding of **SOC formation pathways** and **pool-specific saturation deficits** in conventional farming as opposed to innovative systems is insufficient according to the Central region. The Western region states that a life cycle analysis of different agricultural systems to evaluate their overall performances relating to SOC sequestration and GHG emission would benefit current research efforts. In these regards, BE-VLG emphasised the SoilGen model, which is an integrated model that incorporates the C cycle of mineral soils and feedback mechanisms between SOC, soil properties and agricultural management.

Overall, data on **achievable C sequestration potential** is largely missing, as stated by countries in the Western and Central regions. However, some countries have reported existing estimations. For example, in the UK GHG Inventory, broad estimates of achievable C sequestration in mineral soils are available. FR also estimated the achievable C sequestration of agricultural soils. In BE-WAL, a regional map of stable C sequestration potential was produced, which gives information on the agricultural land that can sequester most C in the future.

The Western region described a need for **simple SOC sampling techniques** for farmers and the identification of the most efficient national policies aiming to improve SOC stocks. A lack of **knowledge transfer** from research into practice and legislation was stressed as a major short-coming by the Central region. According to the Western, Southern and Northern regions, improved knowledge on

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SOC quality and sequestration potentials of pioneer agricultural practices is vital to advise policymakers on determining sustainable soil management options.

There is generally little research available on organic soils in Europe. Accurate **estimations of peatland** and degraded peatland are missing in the Western region. The Northern region needs updated maps on peatland, groundwater levels and C stocks. **Monitoring of peat soils** is needed in the Central region, and monitoring GHG emission and reliable quantification of C loss rates in the Northern region. Further, there is a lack of studies on the protection of organic soils by rewetting in the north and how those rewetted soils can be cultivated without increasing their GHG emissions in the Central region. Within the Southern region, no knowledge gaps regarding organic soils were formulated, which indicates that peatland is less relevant in those countries.

In conclusion, knowledge gaps in C stocks in Europe are diverse, but many similarities across countries and regions could be found. It needs to be acknowledged that not all countries submitted data, hence this synthesis is not complete. Nevertheless, a qualitative analysis of the national inputs was possible, resulting in an overall impression of the European-wide knowledge needs. The most critical knowledge gaps stated by the four regions are presented below (Table 3), not ranked in order of importance. In Table 3, the 10 main knowledge gaps on carbon stocks are displayed. The regions in which the common knowledge gaps were raised are indicated. In Figure 7, and the specific knowledge gaps for each region and knowledge gaps identified in more than one region can be found. The sources of information for both Table 3 and Figure 7 are the national inputs.

Table 3. Ten main knowledge gaps on carbon stocks highlighted in the national inputs (in no specific order of importance; N=North, S=South, C=Central, W=West).

Knowledge gaps	N	S	C	W
Deep soil carbon and its dynamics	x	x	x	x
Impacts of **deep roots** on C stocks	x	x	x	x
Biochar and its potentials	x	x		x
Potential of **organic wastes** and the processes for how to make them safe for use in agriculture			x	x
Insufficient **monitoring** and a need for a common monitoring system on national and international bases	x		x	x
Modelling of SOC	x	x	x	x
Standardised, international, easy-to-use **method for soil C stock assessment**			x	x
C sequestration potential		x	x	x
Processes affecting **SOC in different C fractions**	x	x		
Accurate **estimation and monitoring of peatland**	x		x	x

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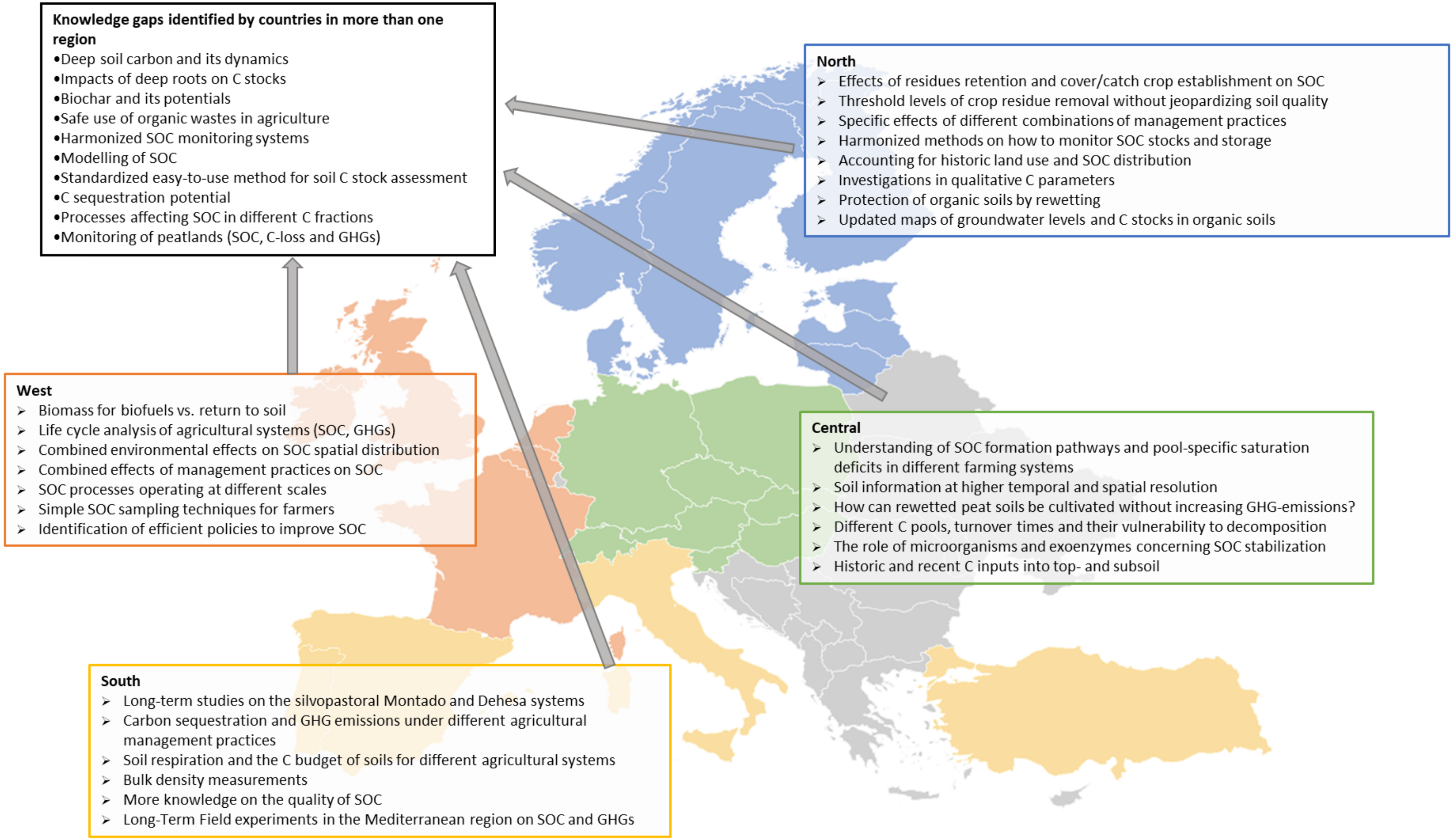

Figure 7. Specific knowledge gaps for each region and knowledge gaps identified in more than one region regarding carbon stocks; source: national inputs.

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4 Soil degradation and fertility

4.1 Review of EU and international projects and literature

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4.1.1 Review of European and international projects

Degraded soils have a diminished capacity to function in a way that supports human needs and ecosystems in general. Global assessments indicate that the percentage of total land area that is highly degraded has increased from 15% in 1991 to 25% in 2011 (UNCCD[1]). Furthermore, on a global scale, the ITPS and GSP initiatives state that 33% land is moderately to highly degraded due to erosion, salinization, compaction, acidification and chemical pollution of soils. Besides these degradation processes, the most severe natural and human-induced threats also include OM decline, desertification, soil sealing and acidification. Due to the large extent of degraded land and areas, reversing degradation into functionally valuable land is imperative (INSPIRATION). According to the IPBES initiative, an urgent step change in effort is needed to prevent irreversible land degradation and accelerate the implementation of restoration measures. In general, there is a need for the development of appropriate degradation and restoration indicators and the strengthening of existing measurement and monitoring programmes. There are inherent problems in extrapolating field measurements from one location to other areas. Current land surface models mostly do not include degraded conditions and can have both a spatial and temporal resolution that is too coarse for application to small-scale degradation. According to the IPBES initiative, the most direct improvement in the assessment of degradation would be a dramatic increase in routine, regular monitoring. The concrete goals for restoration or rehabilitation have to be specified according to, on the other hand, the type and intensity of degradation, and the specific target conditions on the other; the use of general ecological value targets for non-degraded land is inadequate (INSPIRATION).

The ongoing SoilCare project aims to "identify, test and evaluate soil-improving cropping systems (SICS) that will increase the profitability and sustainability of agriculture across Europe". These SICS have been formulated for several degradation threats (i.e., *soil challenges* according to EJP SOIL terminology) (see the different sections below), but the concept and usefulness of the soil threat (soil challenges) -specific SICS still have to be tested.

4.1.1.1 Soil erosion

Erosion is the main soil degradation process in Europe and Central Asia (IPBES), but, the results of the various erosion risk models and approaches that have been applied at the European-scale differ quite considerably. This relates to differences in modelling approaches, differences in model input data and their quality as well as to differences in the models' spatial and temporal resolutions. Concerning soil erosion by water, ~105 million ha or 17% of the total land area of Europe is subject to some degree of soil erosion risk. Furthermore, Europe can be divided into three zones where erosion risk is significant: (i) a southern zone characterised by a severe risk of erosion by water; (ii) a northern loess zone with a moderate risk; and (iii) an eastern zone where the two prior zones overlap. Within all three zones, however, hotspots of soil erosion risk do occur. At the country level, Greece, Italy, Portugal, Italy and Spain stand out with the highest mean annual rates of soil erosion risk. Spain is the country with the largest area subject to a high erosion risk, comprising southern and western Spain and covering 44% of the country's territory. Portugal ranks second, with one-third of its territory revealing a high erosion risk. In Central and Eastern Europe, soil erosion risk is most widespread in Bulgaria and Slovakia, affecting some 40% of the territory of both countries (Stolte et al., 2016, RECARE). Additionally, soil erosion by water dominates and affects 26% of agricultural land in Russia (or 3.5% of the total land)

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and about 30% of agricultural land in Moldova and Ukraine (IPBES and references therein). In relation to soil erosion by wind, preliminary investigations show that areas potentially affected by high erosion levels appear only in specific regions. In the Mediterranean area, susceptibility is high to moderate along the south-west coast of Spain, in the Gulf of Lion and on the Italian, French and Greek islands. In Northern Europe, the most highly susceptible regions are found along the coastal area, i.e., in Nord-Pas-de-Calais and Normandy in France; and parts of the Northern Netherlands. In the United Kingdom, some of the most susceptible areas were estimated to be in south-western England and Scotland. Large parts of Denmark, particularly in the western sector of the peninsula and in the eastern archipelago, also show high susceptibility values. In Sweden, the region of Scania is the area with the highest susceptibility. Severe susceptibility was also modelled along the Romanian and Bulgarian coasts and in the lowlands surrounding the Carpathian Mountains. For the more continental areas, the results show high susceptibility in the Pyrenean and Alpine regions, central Spain and north-eastern Serbia. A few hotspots were identified along the coasts of Germany and Poland, in central France and central and southern Italy. The sectors of the study region that tend to have consistently low susceptibility values are the Baltic States, Finland, Slovenia, Portugal, southern Germany and Ireland (Stolte et al., 2016, RECARE).

Soil erosion by wind is highly dominant in Central Asia, where 23% of agricultural land is affected - nearly 80% of that in Uzbekistan (IPBES and references therein). USDA estimates wind erosion rates of approx. 2.5 t ha^{-1} yr^{-1} on average for cropland in the United States, while the average erosion rate for pastureland is approx. 0.1 t ha^{-1} yr^{-1}. One of the ecosystem services that can be simulated and assessed through the Landsupport tool is protection against soil erosion. The Landsupport interphase will come up with an estimate of the potential soil erosion within a certain area (LANDSUPPORT). Erosion rates are still high on much of the agricultural land of the globe, and this is related to the lack of economic incentives for today's farmers to conserve the soil resource for future generations. Tackling this problem requires the soil erosion problem to be reframed. Erosion by water on sloping and relatively steep lands should be minimised by measures that reduce runoff rates and velocity such as strip cropping, contour planting, crop rotation, intercropping, agroforestry, cross slope barriers (e.g. grass strips, contour bunds and stone lines), terrace construction and maintenance, and grassed waterways or vegetated buffer strips (ITPS and GSP, AGFORWARD, INSPIRATION). Accordingly, the most promising erosion-specific SICS suggested by SoilCare are highly site (morphology), climate (high rainfall areas) and soil specific. Erosion-specific SICS involve a whole range of actions, including a permanent groundcover (crops, mulches), reduced tillage, contour ridging, terracing, drainage, and agroforestry (SoilCare). In relation to water erosion, however, there is an inadequate harmonization on methods for different spatial and temporal scales. For wind erosion, there is a lack of knowledge on where and when wind erosion occurs in Europe and at what point erosion starts posing a threat (i.e., challenge) to agricultural productivity (RECARE).

4.1.1.2 Soil compaction

In Europe, 32-38% of soils have a high to very high susceptibility to compaction (ESP). According to the most recent analysis of soil compaction status in Europe, below-critical densities are found in large parts of Central Europe, while above critical areas are found in parts of the Baltic area, in Denmark, in and around the former Czechoslovakia, in northern Portugal, in Italy, and in parts of the United Kingdom (Stolte et al., 2016, RECARE). One of the important options available in order to improve water regulation and purification is to avoid animal grazing and machinery traffic under wet soil conditions to maintain water infiltration and reduce soil compaction (LANDMARK). The most promising compaction-specific SICS according to the SoilCare initiative are (i) prevention of further densification of the (sub)soil, and (ii) remediation of compacted soils and/or alleviation of their effects. They may involve controlled traffic, adjusting mechanization and the planning of activities, growing deep-rooting crops, and stimulating biological activity through addition of organic matter. According to the RECARE project, there is only limited knowledge on subsoil compaction.

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4.1.1.3 Soil contamination

In Europe alone, there are approx. three million contaminated sites, with 17,000 treated so far. The most common contaminants are mineral oil and heavy metals (ESP). Some pollution problems such as acidification and eutrophication of terrestrial ecosystems have been decreasing in Western and Central Europe since 1990, from 30% and 78%, respectively, of areas exceeding critical pollutant loads of sensitive ecosystems, to 3% and 55%, respectively. The total sales of pesticides across the European Union increased from 2011 to 2014 by 4% to just under 400,000 tonnes of active substances, despite the adoption of the Directive on the Sustainable Use of Pesticides in 2009 (IPBES). In EIP-AGRI it is acknowledged that the implementation of sustainable farm management and soil conservation technologies should help farmers protect their soils from contamination. Pollution-specific SICS according to the SoilCare initiative are directed towards: (i) preventing pollution, (ii) minimizing the mobility and toxicity and/or stimulating the breakdown of pollutants, and (iii) lowering pollutant concentrations in soil through phytoremediation. In relation to contamination, it is further acknowledged that:

- The understanding of the effect of heavy metals on aquatic life is inadequate, and there is a lack of analytical and sampling techniques (RECARE).
- There are missing links between soil laboratory data and their applicability at the farm level to prevent and monitor contamination. This would require the establishment and set up of a soil quality monitoring protocol, which enables the farmers to assess the respective soil status at farm level.
- There are knowledge gaps on plant behaviour and the uptake of contaminants. Identification of alternative crops to be cultivated in contaminated soils is needed (e.g. energy crops, fibre, biomass, etc.).
- There is a need to establish long-term experimental sites to deliver scientific criteria for the long-term efficacy of soil remediation. This would help to assess cost-effectiveness of different remediation methods.
- It is necessary to establish the fate of emerging contaminants such as pharmaceuticals, veterinary and personal care products and define threshold values.
- Standardization/validation of different precision agriculture methods is missing (roadmap for farmers) that would help to make precision agriculture methods usable and affordable for small-scale farmers (EIP-AGRI).
- There is a lack of a harmonised monitoring system for contamination (ESP).

4.1.1.4 Soil organic matter decline in mineral topsoil

At this stage, there is a lack of accurate SOC estimations and lack of tools for scenario analyses for agricultural soils (RECARE). The impact of management practices to increase SOC may take longer than 10 years to show significant changes (JRC). On OM decline there is currently a need to:

- Define SOM reference values related to soil types and functions.
- Design organic carbon analysis standards and databases.
- Develop techniques to study the improvement and/or the fate of SOM in soils, related to carbon inputs from different sources (EIP-AGRI).
- Develop and test innovative practices to avoid SOC loss and increase SOC (4 per 1000).

4.1.1.5 Salinization

Poor maintenance of drainage systems has resulted in millions of hectares of irrigated areas suffering from salinization and waterlogging. In Uzbekistan 51% (2.1 million ha) and Turkmenistan 68% (1.3 million ha) of irrigated areas are salinized and further widespread degradation of agricultural land is expected in these countries (IPBES and references therein). Salinization and sodification affect 3.8 million ha in Europe (ESP). Naturally saline soils occur in Spain, Hungary, Slovakia, Greece, Austria,

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Bosnia, Serbia, Croatia, Romania, Bulgaria, Ukraine and the Caspian Basin. On the other hand, artificially induced salinization is affecting significant parts of Italy, Spain, Hungary, Greece, Cyprus, Portugal, France, the Dalmatian coast of the Balkans, Slovakia and Romania. In addition, North European countries (e.g., Denmark, Poland, Latvia and Estonia) are facing similar issues. North-western Europe (e.g., the Western Netherlands, Belgium, North-eastern France and South-eastern England) is another territory that is affected by soil salinization, which is mainly caused by sea-level rise and surface seawater seepage. Soil salinity that affects mainly the Mediterranean countries is regarded as a major cause of desertification and is therefore a serious form of soil degradation (Stolte et al., 2016 and references therein, RECARE). Since the process of soil salinization can be highly dynamic in space, time and intensity, a continuous innovation in crop, soil, and water management is needed, within the different agricultural systems and local settings (EIP-AGRI). One of the major constrains in modelling and prediction of the spread of salinization is usually the lack of model input data across Europe (RECARE).

4.1.1.6 Desertification

Desertification, land degradation and drought (DLDD) processes have accelerated rapidly in the last century, with an estimated 24 billion tonnes of fertile soil lost to erosion on the world‘s croplands. If the current scenario of land degradation continues over the next 25 years, it may reduce the estimated potential global food production by as much as 12%. Adopting and scaling up sustainable land management practices, both in terms of area and effectiveness, and improving land-use planning and governance structures at the national and local levels are often the most effective ways of overcoming DLDD (UNCCD and references therein). At the European level, 8% of the territory in Southern, Central and Eastern Europe shows very high or high sensitivity to desertification, corresponding to ~14 million ha, and > 40 million ha if moderate sensitivities are included. In particular, the Mediterranean region shows a consistent drying tendency (Stolte et al., 2016, RECARE). Groundwater overexploitation, often due to irrigation, results in a lowering of the groundwater table, which increases the risk of desertification. In addition, the chemical composition of groundwater is often suboptimal for irrigation due to its high salt/mineral or metal content, and irrigation with groundwater often leads to salinization or alkalinisation of the soils (IPBES). The best SoilCare SICS include growing tree lines and hedges to minimise erosion, growing C-4 crops with a high water use efficiency, prevention of overgrazing, and increasing external inputs of water and nutrients. Currently, there are no standardised procedures for assessing desertification, and thus an integrated framework is needed to enable meaningful, repeatable and comparable assessments of desertification (RECARE). The problem of drought impact assessment is further compounded by the lack of data on drought vulnerability and impacts in different sectors, including the costs of indirect and longer-term drought impacts. Very few studies have assessed the benefits of the implementation of drought impact mitigation measures. However, the costs of proactive drought risk management are usually lower than the costs of inaction, hence it can generate significant economic benefits (JRC).

4.1.1.7 Soil sealing

Soil sealing covers about 4% of the total area in the European economic area, but the biggest problem with soil sealing is in Western Europe (ESP). It is likely to remain a threat (i.e., challenge) to natural and agricultural areas in Europe, especially those in the vicinity of existing urban developments (cities, towns) and along the Mediterranean coast, unless national, regional and local governments implement stricter regulations (RECARE). There is inconsistency on land take rate data for soil sealing at the European level due to different methodologies applied by the countries.

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4.1.1.8 Acidification

Regulatory controls initiated in recent decades to mitigate global warming have had a significant impact on the emissions of pollutants that cause acidification, mainly by decreasing SO_2 emissions (ESP project). To avert and reduce the severity of acidification the SoilCare initiative advises replacing acidifying nitrogen fertilisers by nitrate-based fertilisers; applying manures, compost and crop residues, and growing acid-tolerant crops.

4.1.1.9 The impact of climate change

By 2050, land degradation and climate change combined are predicted to reduce crop yields by an average of 10% globally and up to 50% in certain regions (IPBES). Due to the construction of infrastructure for the economy, the risk of and vulnerability to natural hazards and disasters have increased. Thus, human-induced changes in nature such as river straightening, deforestation, agriculture, soil sealing, and drainage of peat have led to an increase in land and soil instability and greater vulnerability towards natural hazards such as floods, forest fires, land subsidence, erosion and landslides. In particular, climate change is expected to increase the severity of these degradation processes (INSPIRATION). Unfortunately, model simulations do not yet take into account the effect of climate change, which will probably have a negative impact such as increasing soil erosion rates in Europe (JRC). Sustainable land management and land restoration are believed to assist climate change mitigation and adaptation (IPBES).

4.1.1.10 Politics

Finally, knowledge on main soil threats (i.e., challenges) and agricultural management practices that are acceptable and easily implemented by farmers should be considered in future policy strategies, either to support farmers already adopting these promising practices to promote soil quality or to establish priorities for future incentives. At this point, the adoption of agricultural management practices to deal with soil challenges is not properly implemented (Barao et al., 2019).

4.1.1.11 Project list

4 per 1000 - Soils for food security and climate

AGFORWARD - AGroFORestry that Will Advance Rural Development

EIP-AGRI - The agricultural European Innovation Partnership

ESP - European Soil Partnership

GSP – The Global Soil Partnership for Food Security and Climate Change Adaptation and Mitigation

INSPIRATION - INtegrated Spatial Planning, land use and soil management Research AcTION

IPBES - Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

ITPS - Intergovernmental Technical Panel on Soils

JRC – The Joint Research Center

Landmark - European Research Project on the sustainable management of land and soil in Europe

LANDSUPPORT - Development of Integrated Web-Based Land Decision Support System Aiming Towards the Implementation of Policies for Agriculture and Environment

RECARE - Preventing and Remediating degradation of soils in Europe through Land Care

SoilCare – SoilCare for profitable and sustainable crop production in Europe

UNCCD - The United Nations Convention to Combat Desertification

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4.1.2 Review of European literature

4.1.2.1 Soil erosion

Erosion in Europe is a combination of erosion by water, wind, and tillage and some management practices (crop harvesting and land levelling) and several studies have attempted to quantify the actual or tolerable erosion using modelling approaches. Using the WaTEM/SEDEM models for the land area in the EU-28, Borelli et al. (2018) found that soil loss in the riverine system was about 15% of the estimated gross on-site erosion. Additionally, sediment yield totals hovered around 4.62 Mg ha^{-1} yr^{-1} in the erosion area. The largest proportion (93.5%) of gross on-site erosion, as well as loss to rivers, happened in agricultural areas. Conversely, forests and semi-natural vegetation areas tended to experience an overall surplus of sediments originating from agricultural land. According to works cited in Verheijen et al. (2009), total erosion rates for arable land in Europe range from 10 to 20 t ha^{-1} yr^{-1}. Of this total, harvesting of root crops (1.3 to 19 t ha^{-1} yr^{-1}) and tillage erosion (3 to 9 t ha^{-1} yr^{-1}) are significant contributors to the total erosion rates. These estimates are significantly higher than the expected tolerable range of 0.3 to 1.4 t ha^{-1} yr^{-1} (Verheijen et al., 2009). Concerning erosion by wind, Borelli et al. (2017) estimate that around 7% of the EU arable lands have a rate higher than 2 t ha^{-1} yr^{-1}. These Europe-wide estimates sometimes mask the local erosion risks for member countries. A study by Bakker et al. (2008) modelled erosion and sediment export to lakes and rivers, in response to land-use changes. The work considered sites in Portugal, France, Greece and Belgium. They showed that during the last 50 years, the extensification of land use in marginal and agricultural areas strongly reduced erosion and sediment export. This trend was greater when erosion-prone land use (arable agriculture) was converted to less-erosion prone land use such as forests. Aside from land use effects, rainfall erosivity is a critical factor in erosion assessment. Panagos et al. (2015) reported that across the EU there is a very large variability in rainfall erosivity (51.4 to 6228.7 MJ mm ha^{-1} h^{-1} yr^{-1}). The Mediterranean and Alpine regions had the highest erosivity values, while Scandinavian countries had the lowest.

4.1.2.2 Soil compaction

Soil compaction affects several soil properties including strength and aspects of the soil pore system such as pore size distribution and connectivity. Soil functions and ecosystem services are negatively affected by this impact of field traffic. Subsoil compaction is effectively persistent. Based on a survey of European subsoils, Schjønning et al. (2016) found that nearly 25% had critically high densities. These soils were found in parts of the United Kingdom, in parts of the Baltic area, in Denmark, in and around the former Czechoslovakia, in northern Portugal and in Italy (Figure 6.1 in Schjønning et al., 2016). A more precise survey conducted in Denmark indicates that at least 39% of Danish agricultural soils have critically high densities in the upper subsoil (Schjønning et al., 2016).

More thorough assessments of the state of soil compaction for European soils is needed (Schjønning et al., 2015), including quantification of the economic and ecological costs of compaction (Keller et al., 2019). In that respect, an improved data basis of the chain of effects from soil stress to root growth conditions and hydraulic properties is highly needed (quoted by Keller et al., 2019). Pulido-Moncada et al. (2019) and De Pue et al. (2020) highlighted the need for more experimental research on the stress transmission under active field traffic including the effects of traction and soil slip on soil compaction. In addition, studies that relate compaction to greenhouse gas emissions are needed (Schjønning et al, 2015).

Keller et al. (2019) and Schjønning et al. (2015) both encourage the development of engineering solutions such as lightweight agricultural machinery or robots to prevent soil compaction. Further, there is a lack of research on how to recover compacted soils (Keller et al., 2019).

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4.1.2.3 Soil contamination

Due to more than 200 years of industrialization, soil contamination is a widespread problem in Europe. The most frequent contaminants are heavy metals and mineral oil (60% of total), and they occur on sites close to landfills, industrial and commercial installations, and military camps. Municipal and industrial wastes contribute most to soil contamination (38%), followed by the industrial and commercial sector (34%). The number of sites where potentially polluting activities have taken place now stands at approximately 2.5 million, and of which identified contaminated sites number around 342,000 (Panagos et al., 2013). There are projections that the number of sites will rise by about 50% by 2025 (Jones et al., 2012; EEA, 2014). Consequently, the average number of contaminated sites/1000 inhabitants across the region depends strongly on past and present industrial and commercial activities. While the NL, BE, DK, FR, DE and UK averaged higher than 2.46/1000 inhabitants, other countries like Greece, NO, IE and IT are much lower (Panagos et al., 2013).

Aside from the localised contaminated sites, diffuse soil contamination is also a threat (i.e., challenge) that may be barely apparent or not apparent at all. Diffuse soil contamination results from the presence of inorganic compounds such as metallic trace elements and radionuclides, and organic compounds such as natural and xenobiotic molecules and the overuse of sewage sludge (EEA, 2012). In France, diffuse contamination with heavy metals was associated with sewage sludge amendments. While in the Mediterranean (ES), Co, Cr, Fe, Mn, Ni and Zn in agricultural soils have been associated with parent rocks, the presence of Cd, Cu and Pb is related to human activities (Micó et al., 2006).

The use of pesticides in agriculture is also a potential source of soil contamination. Silva et al. (2019) analysed 76 prioritised pesticides in six cropping systems across 11 EU countries. Pesticide residues were absent in only 17% of the tested agricultural topsoils. Residues of single pesticides were observed in 25% of topsoils, while 58% of the topsoils contained multiple pesticide residues. Southern Europe had significantly fewer residues than the Northern, eastern and western regions. The highest frequency of soils with pesticide residues was found in Eastern Europe. In terms of prevalence of pesticides in crop types, soils grown with root crops had significantly more residues that the soils from other crops. The soils revealed a high diversity of pesticide combinations; of the 166 pesticide combinations, 150 corresponded to mixtures of ≥2 residues. The most common compounds in soils (present in >10% of soil samples) were AMPA, boscalid, epoxiconazole, DDE pp., glyphosate and tebuconazole, and these were also the compounds with the highest detected concentrations in soil. Glyphosate and/or AMPA were present in 45% of the topsoils.

4.1.2.4 Soil organic matter decline in mineral topsoil

Loss of SOM is seen as a main threat (i.e., challenge) to sustained soil functions and services on the European scale (Morari et al., 2016) since SOM affects a range of important soil properties. However, knowledge about the extent of SOM decline as a threat (i.e., challenge) for a range of soil functions across Europe is lacking. Thus, one major unresolved issue is the identification of an appropriate level of SOM in soil. If an appropriate level of SOM could be identified, it would be possible to identify risk areas and hence prevent exhaustion of vulnerable soil and instead secure soil functions and services by sustainable farm management (Jensen, 2020).

A range of studies have indicated that the clay/soil organic carbon (SOC) ratio can be used as an indicator of soil structural stability and quality (Dexter et al., 2008; Getahun et al., 2016; Jensen et al., 2017; Jensen et al., 2019; Johannes et al., 2017; Schjønning et al., 2012; Soinne et al., 2016). The studies identified a critical clay/SOC ratio close to 10, which means that soil physical properties were impaired when the clay/SOC ratio was larger than 10. Recently, Prout et al. (2020) related the ratio to the soil structural quality of soils from England and Wales and found that the structural quality decreased with an increase in the clay/SOC ratio. However, they also mention that the quality of their data on soil structure was rather poor. The concept has only been tested to a limited extent and only on arable mineral soils from the following pedo-climatic zones of Europe (defined in Metzger et al., 2005): Boreal, Atlantic North, Atlantic Central and Continental. Merante et al. (2017) applied the concept at European scale, but without relating the clay/SOC ratio to soil physical properties. However, they showed that the clay/SOC ratio, in general, was larger (>20) in the Southern part of Europe, which may indicate poor structural quality. Therefore, there is a need to evaluate the concept of some soil properties from other climate regions, especially in Southern Europe. Studies on different soil types, clay mineralogy and where the clay/SOC ratio is related to other soil functions would also improve the applicability of the concept.

Critically low SOC concentrations may be expected to compromise the capacity of the soil to support crop production, e.g., through negative effects on soil structure. However, an analysis of long-term field experiments distributed throughout Europe showed an insignificant effect of SOC on crop yield not restricted by any nutrient (Hijbeek et al., 2017), although they found that for specific crops such as potatoes, maize and spring-sown cereals a high SOC content was related to increased optimal yield. More studies on the effects of SOC and the clay/SOC ratio on crop yield not restricted by nutrients are needed.

There is also a need for studies investigating soil recovery including best management strategies to increase SOM and improve soil functions. A study has shown that a substantial time was required before a change in SOC and soil pore structure following conversion of arable land to grassland could be observed (Jensen et al., 2020a; Jensen et al., 2020b) but that immediate effects on macro-aggregate stability were found (Jensen et al., 2020a). Thus, this soil improvement strategy may not be as effective as assumed with respect to increasing SOC and improving soil pore structure, and there may be a time lag that we need to be aware of.

4.1.2.5 Salinization

Soil salinization is a broad term that includes three soil conditions: (i) high salt concentration – saline soils, (ii) high sodium concentration – sodic soils, and (iii) high amounts of carbonates, expressed as increased pH – alkaline soils (van Beek and Tóth, 2012). European soils account for about 30.7 Mha or 3.3% of the global saline and sodic soils (Rengasamy, 2006), the majority of which is found in the Mediterranean region (Geeson et al., 2003). Naturally saline soils occur in Spain, Hungary, Slovakia, Greece, Austria, Bosnia, Serbia, Croatia, Romania, Bulgaria, Ukraine and the Caspian Basin. In addition, salinity arising from seawater intrusion has been observed in the Western Netherlands, Denmark, Belgium, North-eastern France, and South-eastern England (Raats, 2015; Trnka et al., 2013; van Weert et al., 2009). Secondary salinization, caused by anthropogenic activities, affects around 3.8 to 4.0 Mha of soils in Europe (Stanners and Bourdeau, 1995; van Camp et al., 2004). Anthropogenic-driven salinity is present in Italy (e.g., Campania and Sicily), Spain (e.g., the Ebro Valley), Hungary (e.g., Great Alfold), Greece, Cyprus, Portugal, France (West coast), the Dalmatian coast of the Balkans, Slovakia, Romania, and North European countries such as Denmark, Poland, Latvia and Estonia. In the Mediterranean region, soil salinization affects 25% of irrigated agricultural land at a significant level (Geeson et al., 2003; Mateo-Sagasta and Burke, 2011). The negative impact of salinization is more strongly felt in coastal Southern Europe due to the increased abstraction of groundwater for agricultural activities – a catalyst for seawater intrusion (Daliakopoulos et al., 2016).

4.1.2.6 Desertification

Desertification, a form of land degradation in drylands, is a growing threat (i.e., challenge) in the EU with significant effects on the use of land. The term often describes human- and climate-related processes leading to problems affecting dry areas, such as diminished food production, soil infertility, decreases in the soil's natural resilience, and reduced water quality (EU, 2018). The Desertification Information System for the Mediterranean (DISMED) reported that, in general, the desertification problem in Europe is less than in neighbouring regions. However, the problem is pronounced in the

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Mediterranean regions of the EU (southern Portugal, Spain, and Greece) and areas adjacent to the Black Sea in Bulgaria and Romania. In the Southern, Central and eastern parts of Europe, about 8% of the land area shows high or very high sensitivity to desertification – amounting to about 14 million ha (Jones et al., 2012). Five years on, after the DISMED report, Prăvălie et al. (2017) updated the Sensitivity Desertification Index across Europe. They found that in Europe, Spain was the most threatened country to desertification, followed by concerns for the other countries already listed above. The areas highly prone to desertification in the aforementioned countries were found to be up to four times larger than estimated from DISMED.

4.1.2.7 Soil sealing

Soil sealing is not described in pan-European scientific literature. In Siebielec et al. (2016), the soil threat (i.e. challenge) is described, and a map of Europe with percentages of soil sealing is shown. The article also states that the sealed area in Europe is increasing by around 1000 km^2 per year.

4.1.2.8 Acidification

Soil acidification occurs due to a build-up of hydrogen and aluminium cations in soils or the leaching of basic cations (K^+, Ca^{2+}, $Mg^{2+,}$ Na^+) and their replacement by H^+ or Al^{3+}. In general, acidification is an issue only in some highly urbanised or industrial hotspots (EEA, 2010). The main culprit of anthropogenic soil acidification, emissions of acidifying pollutants, has declined significantly over the years. The effect of this reduction on soil acidity and acidification is still unclear; some studies show a clear decrease in soil acidity (Jones et al., 2012; EEA, 2012), while others indicate limited reductions or no effect on soil acidity. In forested soils, critical limits of soil acidification were significantly exceeded in 25% of investigated sites (Fischer et al., 2010).

4.1.2.9 Overall summary

An overview of the knowledge gaps and research recommendations identified based on the review of European and international projects and the review of European literature for each soil threat (i.e., challenge) can be seen in Table 4.

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Table 4. Overview of knowledge gaps and research recommendations for soil threats (i.e. challenges)

Soil threats/ challenges	**Knowledge gaps or research recommendations**
Soil erosion	• Improving the database of sediment yield (SY) measurements. • Utilizing the JRC soil sample database to integrate fallout radionuclide derived soil erosion and deposition rates in large-scale modelling. • Consideration of all erosion types (wind, water, tillage, crop harvesting, land levelling, etc.) when deriving estimates of soil erosion rates in a soil monitoring system. • Research into more spatially differentiated evidence of current erosion rates. • Deeper understanding of other erosional processes such as piping erosion, soil loss by crop harvesting and gully erosion. • Harmonization of data on actual erosion rates for Europe, and standardization of national erosion measures and estimates. • Lack of economic incentives for today's farmers to conserve the soil resource for future generations. • Inadequate harmonization on methods to use for spatial and temporal scales. • For wind erosion there is a lack of knowledge on where and when wind erosion occurs in Europe and uncertainties about the intensity at which erosion poses a threat to agricultural productivity.
Soil compaction	• More thorough assessments of the state of soil compaction for European soils. • Quantification of the economic and ecological costs of compaction. • Improved knowledge of the chain of effects from soil stress to root growth conditions and hydraulic properties. • More experimental research on the stress transmission under active field traffic including the effects of traction and slip. • Studies that relate compaction to greenhouse gas emissions. • Development of engineering solutions such as lightweight agricultural machinery or robots to prevent soil compaction. • Research on how to recover compacted soils. • Limited knowledge on subsoil compaction.

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Soil contamination	• Lack of harmonised requirements for collection of data on diffuse contamination across EU member countries. • Future pesticide field monitoring assessments should consider residue distribution at different topsoil depths and should focus on the uppermost 1 cm of the soil surface layer. • Sampling in early spring, immediately before the first pesticide applications, should provide a better indication of background values of currently used pesticides. • Knowledge of effect of heavy metal behaviour on aquatic life is inadequate, and there is a lack of analytical and sampling techniques. • There are missing links between soil laboratory data and their applicability at the farm level to prevent and monitor contamination. This would require establishment and setting up of a soil quality monitoring protocol, which enables the farmers to assess the respective soil status at farm level. • There are knowledge gaps in plant behaviour and the uptake of contaminants. Identification of alternative crops to be cultivated in contaminated soils is needed (e.g., energy crops, fibre, biomass, etc.). • There is a need for establishing long-term experimental sites to deliver scientific criteria for the long-term efficacy of soil remediation. This would help to assess cost-effectiveness of different remediation methods. • It is necessary to establish the fate of emerging contaminants such as pharmaceuticals, veterinary and personal care products and define threshold values. • Standardization/validation of different precision agriculture methods is missing (roadmap for farmers) that would help to make precision agriculture methods usable and affordable for small-scale farmers. • There is a lack of a harmonised monitoring system for contamination.
Soil organic matter decline in mineral topsoil	• The extent of organic matter decline as a threat to a range of soil functions across Europe is unknown. • More thorough evaluation of the clay/soil organic carbon (SOC) ratio as an indicator for soil functions, especially in Southern Europe. • More research on the effects of SOC and the clay/SOC ratio on crop yield not restricted by nutrients. • Lack of accurate SOC estimations and lack of tools for scenario analyses for agricultural soils. • Definition of soil organic matter (SOM) reference values related to soil types and functions. • Design of organic carbon analysis standards and databases. • Development of techniques to study the improvement and/or the fate of SOM in soils, related to carbon inputs from different sources. • Development and testing of innovative practices to avoid SOC loss and increase SOC.
Salinization	• Understanding of the carbon dynamics in saline soils, to map fully the effects of salinity on soil function. • Exploration of the potential of satellite imagery to estimate the extent of salinization for monitoring purposes. • Development of a no-regret index for quantifying salinization since most current research is very case-specific. • Improving the consistency and comprehensiveness of the datasets relating to salinization in Europe. • Need for continuous innovation in crop, soil, and water management, within the different agricultural systems and local settings.

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	• Lack of model input data across Europe hampers modelling and prediction of the spread of salinization.
Desertification	• Inadequate use of desertification data collected by member states. • Steps taken to combat desertification in the EU lack coherence. • No agreed methodology for assessing desertification within the EU. • An integrated framework is needed to enable meaningful, repeatable and comparable assessments of desertification. • Lack of data on drought vulnerability and impacts in different sectors, including the costs of indirect and longer-term drought impacts. • Assessment of the benefits of the implementation of drought impact mitigation measures.
Soil sealing	• Inconsistency in land take rate data for soil sealing at the European level due to different methodologies applied by the countries.
Acidification	• Lack of a systematic national and continental-level studies on soil acidification for non-forested soils. • Consideration of the impact of increased NO_x and NH_3 as new acidifying agents.

4.2 Synthesis of national inputs

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The soil degradation and fertility synthesis is based on state-of-the-art knowledge and the knowledge gaps provided by the country members of EJP SOIL. The information collected from national inputs is summarised below and grouped according to the four main European regions defined in section 1.1 of this report (Figure 4).

4.2.1 Northern region

The following synthesis is based on NO, DK, FI, LV, SE and LT inputs. EE did not submit their contribution to this report in time.

The main soil challenges selected by these countries in the Northern region were ‘maintain/increase SOC’, ‘avoid soil erosion’, ‘optimal soil structure’, ‘enhance soil biodiversity’ and ‘enhance soil nutrient retention/use efficiency’. For DK, FI and LT challenges also N_2O/CH_4 emissions’ (including SE), ‘soil contamination’ and ‘water storage capacity’. ‘Avoid peat degradation’ was a concern in DK, FI, NO and SE, whereas ‘soil salinization’ and ‘soil sealing’ were challenges to LT.

A **decline in SOM** due to monoculture and intensive tillage was identified by DK and LT to directly affect soil structure, whereas NO highlighted its influence on crop yield – with a higher reduction in areas where SOM was high originally. LT has quantified a declining trend of soil C-storage in the agricultural soils at small scale and expressed concern over the need for increasing the soil C-sequestration rate. LV reported an increasing SOM decline in agricultural soils, with a current 30% of the total area showing a low level of SOM. An index involving the SOM/clay/aggregate stability relationship was mentioned by DK as a potential indicator for sustainable levels of SOM. LT highlighted the importance of evaluating SOM retention of soils with low buffering capacity and sorption and containing a high level of toxic elements such as Al^{+3}. LT also recognised the need for studies to

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quantify SOM losses. SE reported an increase in SOC concentrations in mineral soils in the last three decades, which is related to an increase in the use of forage crops. Additionally, SE mentioned having extensive knowledge of efficient practices on C sequestration in croplands. Knowledge gaps remain on the extent and severity of SOM decline effects on soil structure degradation, as does an assessment on the dynamics in SOM/clay mineral interactions and of crop rotation/intercropping alternatives to enhance SOM for Nordic-Baltic conditions.

In DK, **peatland degradation** occurs as a result of drainage and tillage. The ongoing research effort in DK is focussed on the quantification of current peatland cover and the effects of agricultural peatland management. NO mentioned that peat inversion is used in cultivated organic soils.

In the Northern region, **soil compaction** is mainly caused by heavy traffic in wet soils – being exacerbated in soils with low SOM (DK, FI and SE) – and affects soil properties and yield while also increasing the risk of other forms of soil degradation (NO). This is a rising problem in the region as increasingly heavier machinery and precipitation intensity (climate change) are likely to increase. Research conducted in DK, NO and SE has identified mechanical stress impacts in deeper layers (>0.6 m depth), and have generated knowledge on topsoil and subsoil compaction drivers, as well as on the compaction effects on soil productivity and soil functions. DK highlighted ongoing research on stress transmission in the soil profile and alleviation strategies. The Terranimo model for planning mechanical operations was developed by DK and adapted to NO and SE conditions. SE has implemented a soil compaction monitoring programme since 2003 that allows quantification of compaction impacts on agricultural soils.

Crucial knowledge gaps identified by DK are soil compaction/yield effects at different soil types/climate conditions; efficient techniques for subsoil compaction mitigation (also pointed by FI); soil compaction-intelligent traffic development based on machinery/soil interaction knowledge; updated data on the extent and severity of soil compaction (also by SE); the impact of soil compaction in a changing climate. SE also pointed out the need to quantify the cost involved for farmers and society of soil compaction. In DK, work on soil structure includes modelling, but there is no regulation to protect from soil structure degradation. FI recognised that there is knowledge available on the impacts of management practices on soil structure; however, it is not clear how to apply this knowledge when making field operation decisions. FI recognised the need for studies on the persistence of the effects of soil compaction, and comprehensive studies on how to monitor soil structure impact. SE recognised the need to extend its monitoring programme to other soil physical and biological properties.

Large **soil erosion** problems are the result of extensive land levelling and intensive arable grain production in South-Eastern NO. Although measures to reduce runoff are extensively applied, monitoring data shows that soil and nutrient losses are high in NO. High nutrient losses are mainly associated with increased frequency and intensity of extreme rainfall events. In DK, wind erosion is, currently not considered a main soil challenge due to well-implemented mitigation measures (hedgerows, cover crops etc.). Nevertheless, studies are needed on the impact of land use and climate change on wind erosion. Water erosion and sediment yield were recently modelled at a national scale in DK, but model validation is needed in order to contribute to conservation planning. In DK, studies have assessed the P- and pesticide transport to water bodies at experimental plots level, but a national scale data collection and monitoring programme is needed. Tillage erosion is considered to be of significant importance in DK, yet assessment of the long-term impact of tillage erosion on soil productivity is lacking. DK also recognised the need for modelling wind and tillage erosion at a national scale. Historical soil erosion maps in LV show that 12% of the agricultural lands are affected by water erosion. LV additionally stated that there is a need for assessment and quantification of the different soil degradation processes that occur in the country. An ongoing Land Policy Plan in LV is expected to help in the release of new regulations on Land and Soil Degradation Criteria and Assessment. FI

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manifested that although efficient practices to control soil erosion are known, their effective applicability under varying conditions is less understood; therefore, studies on soil erosion control integrating different, e.g. farming practices, soil properties and weather dynamics, are needed.

DK stated that the knowledge on soil **water storage capacity** was recognised as satisfactory; i.e. good knowledge on water retention for different soil types. However, there is a lack of knowledge about the root zone; i.e., there are knowledge gaps associated with root growth in relation to soil structure/soil type/soil profile variability/in-season soil water dynamics and how that affects water and nutrient utilisation. LT mentioned the use of soil mulching with the main purpose of enhancing SOM and nutrients, as well as reducing water evaporation. FI also reported a sufficient level of knowledge on practices to increase water storage capacity, though it stated that the effectiveness of two-stage drainage channels in retaining water is up for debate.

Regarding **soil fertility**, LT documented the dominance of a limited crop range (short rotations/monocultures), and the lack of perennial grasses in their crop rotations, which negatively affect soil structure and nutrient status. LT focussed on the use of organic fertilisers, recognising the potential risk of incorporating heavy metals and persistent organic pollutants in the soil, although it is a topic classed as needing research in LT and DK. The degradation of soil fertility due to the use of synthetic agro-inputs is another knowledge gap stated by LT. Soil nutrient retention research in DK has primarily focussed on supporting policy actions to reduce N and P loss. Yet, monitoring programmes at catchment level are needed to target the regulation of N and P. There is also a need in DK for mapping of P mobilisation potential in representative peatlands, and monitoring P-loss on relevant peatland types under different hydrological regimes to assess long-term effects of rewetting projects. On the other hand, LV reported a deficit of phosphorus and potassium in the agricultural soils, as well as an increasing level of soil acidification, which demands liming management. P losses are also a challenge in FI; and there is a need for monitoring programmes of, e.g. S, Mg, B, Cu, and K, which often limit plant growth.

FI recognised that, in terms of **soil contamination**, the use of bio-based fertilisers (e.g. wastewater sludge) could be a source of pollutants in agricultural soils, and there is no knowledge on their potential impact on the food chain. Additionally, acid sulphate soils in FI were cited as a source of heavy metals in surface waters. FI called for studies on the impact of microplastics, heavy metals, organic compounds and antibiotic-resistant bacteria in agricultural soils. Studies on the biogeochemical cycle of Cd and monitoring of recycled/bio-based fertilisers were also stated by FI as a research need in order to control soil contamination. Soils in FI were described as naturally **acidic**, which necessitates regular liming.

Although **Soil biodiversity was** identified as a challenge by DK, FI, LT and NO, no knowledge availability was discussed in the collected inputs. DK, however, mentioned that there is little focus on effects of soil degradation processes on soil biodiversity and on the quantification of ecosystem services of soil biodiversity, for which studies are needed, as well as a monitoring programme on soil biota parameters. FI pointed out the need for comprehensive studies on microbial community functionality and identification of factors affecting them.

Soil sealing was not reported as a soil challenge by the participant countries in the Northern region, though FI stated that this could be of significant importance at a local scale.

4.2.2 Southern region

The main soil challenges considered by all the countries of the Southern region are to 'maintain/increase SOC', 'avoid soil erosion', 'enhance soil biodiversity', 'enhance soil nutrient retention/use efficiency' and 'water storage capacity'. 'Contamination' was a common concern for PT

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and TR, as 'optimal soil structure' was for IT and TR. 'N_2O/CH_4 emission's is a challenge considered by TR and ES, whereas 'soil sealing and salinization' are concerns for IT and PT, ES, respectively.

IT mentioned that **SOC contents** in the country are affected by soil erosion. They also linked the SOC loss with a decline in soil biodiversity, soil structural quality and infiltration capacity. TR has established a topsoil SOC geospatial database, from which a national SOC map and SOC stocks maps have been generated and recently updated. TR reflected that although sufficient research has been conducted on land degradation and soil fertility, more research is needed on management, modelling and monitoring of SOC based on long-term experiments at different scales and for different climatic conditions.

Studies from central PT have shown that the N_2O **emissions** in vineyards are overestimated in the Portuguese inventory and that inter-row permanent soil cover reduces soil N_2O emissions. PT identified the need for further studies on direct N_2O emissions from vineyards to support the present findings. IT has found that the use of organic fertilisers –including animal manure and biochar –show a high potential for reducing GHG emission and energy use. ES also reported significant overestimations in GHG emissions, especially for rainfed agrosystems, and also indicated that some agricultural practices aimed at improving soil fertility could result in increases in GHG emissions.

In vineyards, IT recognised the use of heavy machinery as being responsible for **soil compaction**, which likely influences soil erosion and its related degradation processes. National studies in IT have shown that soil compaction in arable seasonal crops could be prevented by taking into account the soil moisture content in the tillage period. Research conducted in IT raises the interest for large-scale studies on traffic effects on subsoil compaction, and the consequent effects on water balance (subsurface runoff and water input). No further inputs on soil compaction were highlighted by the other countries of the Southern region, yet TR mentioned that dissemination of research and applications of conservative soil tillage and direct seeding are conducted with different crops in different regions of the country. TR is currently investigating the effects of different soil tillage techniques on crop yields and soil properties in a national project.

TR reported increased knowledge of the intrinsic and external factors causing land degradation in the country. TR recognised that climate and topography are important factors causing soil degradation in the country, and key drivers for further potential exacerbation of land degradation under foreseen scenarios in a changing climate. The provided input by TR pointed out that wind erosion is not of a major problem today, as successful prevention and combating measures have been taken for decades, and current agricultural activity takes place in previously affected areas. On the other hand, **soil erosion** by water is still a soil challenge in TR, for which several studies have been conducted − soil erosion on a national scale and soil erosion modelling at different watershed scales. TR mentioned that they have a water erosion atlas and database. In IT, although terrace farming is widely distributed within the country and is an effective controlling strategy for soil erosion, it is still a challenge in hilly areas as unfavourable management practices are applied. IT also mentioned that very few studies have focussed on the relationship between soil erosion and soil function losses. PT considered soil erosion to be one of the main soil challenges in the country, but only referenced soil erosion effects on nutrient loss as is discussed below. ES highlighted that 25% of the total agricultural area exhibits soil erosion with soil loss of >10 t ha^{-1} $year^{-1}$, vineyards and olive farms being the most vulnerable to soil erosion. Estimation of soil loss under climate change seems challenging in ES regions with inter-annual climate variability. Implemented management practices in ES are using cover crops and organic mulching, and are minimizing plant cultivation on slopes, though more comprehensive research is needed on the impact of cover crops and mulching on different aspects of agricultural systems.

TR in their report on **water management** status highlighted that research projects have provided knowledge on the effectiveness and feasibility of different water-saving techniques, allowing recommendation of selected techniques for prevention of soil erosion and enhancing moisture

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retention. The country has an ongoing project to develop plant irrigation for different crops and in different climatic regions by using water-saving irrigation methods. Since irrigation is widely used in many agrosystems in ES, several techniques, such as ultra-low flow emitters, subsurface drip irrigation, smart irrigation scheduling deficit irrigation or regulated deficit irrigation, have been tested to improve water use efficiency, reduce nitrate leaching and avoid salinization.

PT had identified that 45.6% of the total area needs soil restoration – well-planned use and management – to attain their national Land Degradation Neutrality goal. Areas with more sensitive classes of soil restoration in PT are under eucalyptus, vineyards, or recently burned areas. PT reported that **salinization** is not currently a major problem in the southern part of the country, but the potential risk of sodification exists. Hence, PT highlighted two main needs: i) the establishment of monitoring programmes and modelling of the salinization and sodification status, and ii) the identification and application of alleviation actions on degraded areas. TR reported that soil salinization and acidification are main challenges in specific regions of the country, which is the reason why some studies have focussed on management measures for mitigation of the challenges. ES mentioned that up to 25% of its territory is subject to soil loss rates higher than 10 t ha^{-1} yr^{-1}. This is due to stormy rainfall events in zones with low rainfall regime and limited plant cover. High soil erosion rates were reported for olive groves. Soil degradation is also caused by the expansion of irrigated areas, partly on salty and poorly structured soils. Salinization of effluents and the fluvial network is a concern in these regions of ES. The causes of salinization in ES are well known, but there is a need for estimations of the extent and degree of soil salinity in irrigated and dry areas, and research on salinity mitigation impact on soil physical properties.

Regarding **soil fertility**, IT calls attention to efficient fertilisation by farmers based on the application of bio-physical soil knowledge/model N and P predictions, in order to reduce N leaching and costs for the farmer. In PT, studies have shown that the use of organic amendments increase P-use efficiency and decreases P-loss by erosion. A P rate fertilisation plan has been developed in PT from monitoring areas. Site-specific K fertiliser management in pastures has been implemented after the evaluation of spatial and temporal soil K variation. However, research in the southern part of PT suggests no significant correlation of the spatial and temporal variability of P and K in the soil and plants. For soil fertilisation schemes, research in central PT has found that band application of acidified slurry could be a good alternative to raw slurry injection. Ongoing studies in TR are expected to deploy the national map for the FAO's Global assessment of SOC sequestration potential programme, the map of plant nutrient and potentially toxic elements contents of agricultural soils, and identification of heavy metal elements involved in soil contamination. In TR, other ongoing projects on sustainable agricultural practices are expected to contribute to increasing soil quality and soil fertility at a local and regional scale.

Precision agriculture has been used in Portuguese vineyards and pastures to increase the efficiency of soil fertilisation with geo-referenced zones. PT realised the need for long-term measurements of precision agriculture, taking into account the spatial variability of soil P and K in vineyards and pastures. The precision of herbicide application in IT has reported a saving of 29% of applied herbicides amounts, which might also reduce pollution of soil and groundwater.

PT brought up the need for studies on **soil biodiversity** to evaluate the role of microorganisms in the soil to prevent degradation and improve soil productivity.

Lastly, **soil sealing** was considered by IT and highlighted as a big problem in some areas of the country by sealing an annual average of c. 8%. No further inputs were provided on this matter.

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4.2.3 Central region

The major soil challenge mentioned by all participating countries in the Central region is to maintain/increase SOC. The following soil challenges are also of major concern: 'avoid soil erosion', 'optimal soil structure', 'enhance water storage capacity' followed by 'avoid soil sealing', 'avoid contamination', and 'enhance soil nutrient retention/use efficiency'. 'Avoid N_2O/CH_4 emissions' is determined crucial in AT, CH and HU. 'Enhance soil biodiversity' is of high relevance in AT, CH and SK. 'Avoid acidification' is reported as a soil challenge in SK, PL, and AT. 'Avoid peat degradation' is regarded as a main soil challenge in CH, whereas 'avoid salinization' has not been identified by any country in the Central region as a major soil challenge.

In this region, several countries conduct **SOC** stock monitoring and assessment; hence, plenty of information is available. Studies in CH, HU and AT have found that SOC levels were at or are close to steady-state. Data is available in, e.g., SK on qualitative parameters (labile structures of SOM) and stabilisation of SOC in the soil is presented in relation to soil type. Research in SK reveals a slight increase of labile structures of SOM, especially on Cambisols, the most extensive soils in SK. According to CH, SOC contents may increase the number of workable days per year and are thus reducing the risk of tillage operation in wet soils. However, one factor which can trigger substantial changes in SOC is management. Looking at different production systems in CH, topsoils lost SOC despite levels being expected to increase with some treatments (no-till, reduced tillage, organic amendments, organic farming). Also, in HU, a decrease in SOC content is observed in small areas. The reason for this is mostly due to unfavourable agricultural practices (stubble burning, failure to return crop residues, abandonment of organic fertilization, etc.). In addition, areas affected by erosion see a loss of soil organic matter.

In CH, extensive research is ongoing to understand rates and drivers of **N_2O and CH_4 emissions**, and likewise in AT. However, measuring points are scarce, but different modelling tools are used (e.g., LandscapeDNDC) for estimation of N_2O losses. Latest study results reveal that emissions decrease with decreasing farming intensity (highest N_2O losses with conventional management systems > lowest annual N_2O emissions with organic farming due to low N input and a more diverse crop rotation affecting the N balance). These findings support the environmental programme established, which among other things promotes reduced inputs of N fertilisers. HU advocates increasing the efficiency of agricultural production by increasing the SOM content. Also, tillage practices need to be changed, including carbon-saving and moisture-retaining cultivation. AT reported that rising rates of CH_4 emissions from peat bogs are of minor importance since such landscapes are not widely distributed in AT. However, studies of pine peat bog and grasslands in the Alpine South area in AT revealed that CH_4 fluxes follow clear seasonal patterns, which strongly depend on soil temperatures. Overall, peat degradation should be avoided as it releases large amounts of CH_4 following agricultural cultivation (AT).

Regarding **peat degradation**, in the central region the original extent of peat bogs has decreased substantially, mostly by degradation due to large-scale drainage and historical peat extraction. In CH, the degradation status of the remaining peat can be assessed by a stoichiometric method. To prevent the extinction/actively enhance the situation, projects in AT are initiated to survey the remaining peat bogs. In order to be able to protect and restore them, precise knowledge of the current state and condition is necessary. Therefore, monitoring is conducted, and detailed inventories with specific strategies are developed in different projects. Nevertheless, AT reveals that even in protective areas man-made impact (e.g., groundwater recession, eutrophication) is noticeable.

Numerous aspects are investigated in several countries in relation to **soil structure** and **soil compaction** (SK, AT, CH, DE). The formation and degradation factors of the soil structure are well known, as stated by CH. The central region countries also recognised that soil compaction occurs due to the use of heavy machinery in intensively managed arable land and in grassland due to intensive

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cattle grazing. In AT, different methods and models are available to determine soil compaction, and results are displayed as values and maps for the whole country. HU operate with three relevant management steps for soil compaction mitigation: sensible tillage, appropriately timed agro-technical operations, and at the right soil water content. Another tool used to support/enhance soil structure is environmental programmes that promote various measures, such as conservation tillage, organic fertiliser input, and diversity of crops (AT). However, DE pointed out that it is a challenge to obtain optimal soil structure since agricultural soils are compacted, particularly in the subsoil, due to heavy machinery and SOC loss. CH highlighted that the prevalence of soil structural problems is widely unknown, and just occasionally assessed at a local level.

To evaluate the risk of **erosion** in the central region, several measuring tools, methods and models are used. A lot of research has been undertaken to gain insight into the erosion process, e.g., multilevel soil degradation analysis in CZ, monitoring (in AT and CH) and determination of the extent of the threat (in SK, DE, CZ, AT, HU). Factors facilitating erosion, e.g., in HU, are large field sizes and deforestation, in addition to sandy soils and drained wetlands. Estimates in HU rate the loss of topsoil at around 80-100 million tonnes and loss of SOM at about 1.5 million tonnes. In some countries, measures against soil erosion are apparent. For example, in AT where they use a programme for environmentally friendly agriculture and where they have managed to reduce soil loss in areas at high risk of erosion in recent years. Their regulations, however, give no threshold for tolerable soil loss. Long-term experiments in CH revealed a significant reduction in erosion by adapted crop rotations and tillage practice. However, CH recognised that current soil erosion rates outside case study areas are unknown and that erosion rates in managed alpine grasslands usually exceed soil formation rates; hence they are problematic. In AT, farmers pointed out that no-till implementation is limited, and in some cases, access to special machinery (direct drilling) is too expensive, but mulching is practised as it is easily implemented with common machinery. Also, in other countries, erosion control measures are tested and established (AT, CZ, CH). PL reported that quantification of soil water erosion is lacking in the country, but estimations of erosion risk are widely used in policies on erosion prevention.

In AT, measures and guidelines are available for farmers to enhance **water storage capacity** (e.g., cultivation of cover crops). Data for water-holding capacity is available on a soil map (eBOD). In AT, this topic is most relevant in the dry area. In CH, at least 20% of the agricultural land is drained to make it suitable for cultivation and to prevent waterlogging. Increasing concerns about the environmental impact of the drainage systems have triggered research activities, and alternatives to drainage renovation are assessed. HU reported that the country has a severe problem with soil water management as 43 and 26% of the soils have unfavourable and medium water management, respectively. The causes given for unfavourable water management were extremely high sand content, clay content, salinization, and to a lesser extent swamping or shallow cropland. In HU, 41% of the territory is endangered by inland water. Salinization and structural degradation are directly and largely responsible for the unfavourable water management properties of the soil, which are characterised by an inland water hazard and drought sensitivity.

Regarding **nutrient use efficiency**, in the central region, N and P surpluses have decreased in general over the last decades. The establishment of fertilization standards, guidelines, policies and regulations are tools that promote less fertiliser use and more efficient application techniques for higher nutrient use efficiency (CH, DE, AT). PL reported a generally low availability of P, K, Mg and sulphur in monitored areas during the last two decades. However, recent estimates in CH reveal a net surplus especially of N, P and K. As pointed out by CH, problems exist mainly in arable areas (nitrate leaching) and regions with high animal densities (ammonia emissions, eutrophication of soils and water bodies). High stocking rates also raise nitrate levels in the groundwater, exceeding tolerable values (D). However, various recommendations and measures helping to retain nutrients are promoted. In some countries, management decision tools are available to help avoid losses (AT), as well as monitoring programmes for soil nutrient balances calculation. In SK, research activities are focussed on long-term field

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experiments with different fertilisation treatments, with some focussed on organic fertilisers use and related possible soil contamination. In AT, different studies show an increase in nutrient retention under conservation and no-till, as well as lower nutrient losses when using cover crops. However, a study in CH identified a N efficiency-sustainability dilemma at the plot level, where treatments with a high N-use efficiency lose more soil stock N than those with lower N-use efficiency but higher N losses from the system. In HU, reduction in the use of fertiliser had resulted in a negative nutrient balance (since 1990, nationwide), affecting crop yield and soil nutrient supply capacity. Hence, an adapted nutrient replenishment plan is conducted to meet the needs of cultivated plants, the dynamics of nutrient uptake and the local conditions. AT reported a low rate of available P in 90% of the grassland. CH identified as main knowledge gaps the quantification of nutrient pathways in livestock integrated farming systems, and the establishment of accepted and reliable methods to increase the N-use efficiency with site-specific fertilization. PL highlighted that although the country has a regional plant-available nutrient monitoring programme, they still lack a combined national database.

In this region, CZ, SK, CH, AT and HU investigate and monitor soil **contamination**. Based on the tests performed in HU in the framework of the soil monitoring system (TIM), the toxic elements content in 95% of the soils is below the permissible limit value. Toxic elements content above the limit value occurred only at special sampling sites, near industrial areas, due to local loading. In recent years, pesticide residues have been found in only a few per cent of the soils studied, mostly below the limit value (HU). In CZ, observation areas were established to monitor inorganic pollution of both anthropogenic and geogenic origin. Initiated research projects and activities are focussed on the most contaminated or the most vulnerable soils. Soil contamination research also focuses on indirect methods and remote sensing. In AT, studies are conducted for the most relevant heavy metals (Hg, Pb, Cd, and Cu), Pb and Cu levels being highly relevant in grassland soils. Since the risk from diffuse and local accumulation of pollutants exists, it is necessary to continuously improve implementing regulations and reducing pollutant emissions. However, many pollutants (e.g., heavy metals) accumulate in soils (AT, CH). Slurry and manure applications, as well as contaminated mineral P fertiliser, have been identified as a source of Zn and Cu. Also in AT and CH, investigation and monitoring of historical contamination (different pollutants) is quite advanced but remediation activities are progressing slowly. In general, investigation is needed to establish if remediation is required. In CZ, several studies are focussed on bioremediation. Due to their severity, SK will permanently monitor these contaminated soils.

Soil acidification was stated as a moderate challenge on soils in SK. In AT, the soil map “eBOD” identifies the areas with relevant pH information, e.g., less productive areas of CON and ALS grassland often have a pH < 5, and the ALS area is at risk of acidification. HU reported that around 8% of Hungary's soils are strongly acidic, 18% moderately so and 20% weakly acidic. The causes mentioned are soil-forming rock, leaching of cations from higher levels, excessively high-dose N-fertilization (ammonium nitrate or sulphate, urea) in soils with poor buffering capacity, by-products and wastes of various origins. Another aspect raised (AT) is acidifying substances, especially NOx from traffic sources, which are expected to increase in the future. Natural soil acidity was reported as the major soil challenge in PL, covering up to 50% of monitored agricultural areas. In PL, a reduced rate of liming use is explained by insufficient awareness by farmers and economic issues.

Soil salinization is of minor relevance in the region, e.g., in AT. According to SK, salinization and sodification processes are of the same relative impact in the country. In HU about 8% of the territory is covered by various saline soils, e.g., accumulation of salt and/or salinization in the deeper layers of the soil and stagnant saline groundwater near the surface is at risk of secondary salinization. From an international point of view, strict irrigation water quality standards practically exclude the risk of salt accumulation from irrigation water. Nevertheless, it is expected that with climate change, the rate of salinization will increase and the size of saline areas will also increase.

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In the central region, it is recognised that increased **biodiversity** supports a multitude of ecosystem services. Numerous studies (e.g., in CH) highlight the importance of soil microbial diversity for improving crop yields and NUE as well as for improving the system multi-functionality. Ample information exists on the interaction of soil pH, root mass, organic fertiliser application, nutrient availability, etc. and soil organisms. In AT, participation in environmental programmes facilitates implementation of more diverse crops and/or a higher share of green manure crops in the crop rotations as well as organic farming, resulting in positive effects on soil biodiversity. Microbiological products are used in HU soils, containing a combination of different bacterial strains and a combination of several useful microorganisms (cellulose-degrading, nitrogen-binding, phosphorus-mobilizing bacteria, possibly mycorrhizal fungi).

Sealing of formerly productive agricultural soils is mentioned as a major problem in DE, AT, CH and PL. There is no regular monitoring of soil sealing in PL, although it is estimated that 1,000 ha of agricultural lands are annually converted to other purposes. In AT, information on land use and soil sealing is available via monitoring, and determination of soil functions at the planning stage is becoming more important. In addition, several initiatives and measures in AT show improvement of knowledge and that adequate instruments exist, but they differ in priority setting and are not always valid for the entire Federal State. Political aims (in DE) to reduce the rate of soil to be sealed are barely successful. Overall, how these land-use changes influence the soil functions is rarely investigated in German soil science, beyond some a few studies. According to information from CH, it is possible to unseal soils, and these restored soils may develop favourable conditions for crop growth. However, restored soils have reduced functionality (CH). CH points out in this regard that a nationwide soil map, as well as stringent spatial planning policies, are crucial to protecting the most valuable soils from sealing.

4.2.4 Western region

Major and common soil challenges identified for most of the countries in Western region are ‘maintain/increase SOC’, ‘N_2O/CH_4 emissions’, ‘optimal soil structure’, and ‘enhance soil nutrient retention/use efficiency’. ‘Avoid peat degradation’ is a concern in NL, IE and UK, whereas ‘avoid soil erosion’, and ‘enhance soil biodiversity’ are challenges for BE-VLG, FR and UK. ‘Water storage capacity’ was considered by BE-VLG, FR, UK and NL. ‘Soil sealing’ and ‘contamination’ are challenges also identified by FR, which is the country with the largest area and most environmental zones in the region. The extent of these challenges differs in terms of spatial variability within the countries and in the region.

Throughout Western region, extensive knowledge on soil degradation is available and ongoing, i.e., indicators, mechanisms, drivers and mitigation strategies. BE-VLG expressed the general need to increase monitoring programmes on the identified soil challenges to fulfil (inter)national obligations, with emphasis on the need to quantify the current status of each soil challenge on a detailed scale. In relation to **GHG emissions**, BE-VLG mentioned the need for more insight into GHG emissions from agricultural soils and peatlands, including monitoring, as well as the need for evaluating the off-site GHG balance of organic fertilisers.

Peat degradation was discussed by NL, which reported that deep drainage enables dairy farming on peatlands and organic soils. This consequently leads to dehydration, oxidation and decomposition of peat, as well as promoting GHG emissions, N leaching and soil subsidence. NL highlighted the need to conduct studies on the impact of climate change on peatland degradation.

In Western region countries, **soil compaction** by heavy traffic in wet conditions (and by grazing of animals –also important in IE) is a challenge across different soil types. For all, there is a higher risk of soil compaction by heavy machinery in spring and autumn/winter. Soil tillage, affecting aggregate

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stability, is referred to by the UK as a main driver of increasing areas under soil compaction. IE reported the need for long-term experiments to evaluate soil compaction effects on soil functions and ecosystem services and to identify mitigation management practices. In BE-VLG, a soil compaction sensitivity map (vulnerable regions) and soil compaction risk map (maximal wheel load at the recommended optimal tyre pressure) were developed. The Terranimo model has been adapted to BE-VLG and used to simulate the impact of agricultural machinery, tyre pressure, tyre type, soil types and soil moisture conditions. BE-VLG suggested an integrated approach for remediating (sub)soil compaction and recognised the need for more research on the impact of soil compaction on crop yield and quality, for further investigations on the usefulness of remote sensing, X-ray CT scanning, yield maps, and for tractor engine parameters for detecting soil compaction at field scale. NL identified the need for further quantification of soil structure effects on regional water capacity, and the need for knowledge on the natural resilience of compacted soils.

Soil erosion caused by and causing a decline in SOC is a focus in the national inputs from the UK, where different scenarios (agricultural practices, weather conditions, slope position, temporal scale, among others) have been widely studied. Research from the UK highlighted that erosion model validation calls for fit-for-purpose studies and data collection to improve usefulness and consistency. Both BE-VLG and BE-WAL reported numerous research studies conducted in relation to soil erosion. BE-VLG has deployed potential and actual soil (water) erosion maps. Soil erosion research in BE-VLG has helped in the development of policy decision tools like a soil erosion risk indicator (taking into account current crops and measures taken by farmers) and the risk of soil erosion has decreased as a result of firm legislation. In BE-VLG, two wind erosion sensitivity maps were also developed: a potential and an actual (with the latter taking into account a vegetation factor). In the Western region, several measuring tools, methods and models are used. BE-WAL identified the need for the evaluation of innovative techniques with a high efficiency to avoid soil erosion. Additionally, BE-WAL reported that available knowledge should be better integrated into decision-support tools for the agricultural sector, municipalities and policymakers; existing decision-support tools do not, for example, consider gully erosion. In FR, farmers commonly use soil erosion indicators; however, the need for demonstration trials with combinations of practices to avoid soil degradation and enhance soil fertility is recognised. Although soil erosion is very low in IE at present, IE raises concerns about increased problems with erosion in a future climate where rainfall quantity and intensity may increase.

Regarding **water storage capacity**, NL reported having conducted several projects regarding farm practices and water availability. BE-VLG recognised that a sensitivity analysis of factors determining water-holding capacity is required. In a changing climate, water management optimizing the balance between drainage and water conservation needs to be investigated (BE-VLG). Impacts of (potential) drought events on soil functions and crop productivity need to be studied. An additional need identified by BE-VLG is the modelling of nutrient dynamics related to groundwater dynamics.

In general, the above-mentioned soil degradation processes are associated with lower **soil fertility** in the region. IE has a well-established national soil fertility-monitoring plan, from which they have identified: i) a national nutrient depletion in the last decade – linked to lower fertiliser use, and ii) a general improvement in soil pH on a national scale related to a recent higher rate of lime use. In FR, studies focussed on the soil fertility/soil ecology/soil microbiology relationship have been conducted in the last decades. However, they lack broader comprehensive approaches, including the different types of soil degradation, their interactions, and their impact on soil fertility. This necessitates soil fertility evaluation schemes with a more holistic and multi-criteria approach. In the UK, farmers (in general) recognised that the soil structure protection practices increase SOM and reduce nutrient loss and use of pesticides. Reversing soil degradation and restoring fertility by 2030 is an aim of the UK government's 25 Year Environment Plan. BE-VLG recognised that the current monitoring programme needs improvement (nutrient status of soils is not monitored in an independent and statistically sound monitoring network) as this area is acknowledged as a Nitrate Vulnerable Zone. In BE-WAL, N and P are widely investigated, e.g., via BE-WAL digital mapping of agricultural soil P saturation, and a soil database (REQUASUD) of soil analysis is available. However, there is a need for more studies on how to reduce N and P leaching losses leading to eutrophication. In BE-VLG, an ongoing project seeks to establish an economical and environmentally friendly increased P use efficiency.

Soil contamination was mentioned by BE-WAL as a main challenge in this area. Knowledge gaps for BE-WAL involve a lack of analytical standards for hazardous trace elements occurring in agricultural soils, lack of an evaluation of organic pollutants related to sewage sludge, missing soil contamination monitoring, and a need to expand the quantification of soil pesticide content on different soil types. NL recognised the need for decreasing N surplus. **Soil acidification** was reported by BE-VLG as a challenge that covers 50% of the arable lands and 29% of the grasslands, which has led to a higher risk of nutrient leaching. Quantification of the extent of leaching on acidified soils and how to steer the leaching processes need to be investigated. **Soil salinization**, although not considered a main challenge, is a potential risk in the coastal region of BE-VLG, which could be exacerbated under a future climate change. BE-VLG highlighted the need to quantify the current extent of salinization of soils in Flanders.

FR reported advanced knowledge on **soil biodiversity** through molecular approaches. However, knowledge gaps persist on the functional diversity and the functional roles of soil biota in agricultural soils in this country. IE correspondingly appeals for research and monitoring of soil biodiversity levels and trajectories under different soil/climate conditions. NL recognised that intensive cultivation practices under conventional systems had triggered a decline in soil biodiversity. Agricultural soils in NL were reportedly dominated by bacteria rather than by fungi, which does not positively contribute to the enhancement of diverse soil properties such as soil structure, water and nutrient retention. BE-VLG identified the need for standardised biological indicators and target zones (site-specific), definition of parameters for a healthy soil metabolism, assessment of the interactions among soil management, soil biodiversity, plant growth and crop yield, more comprehensive studies on the soil microbial community (rhizosphere vs. bulk soil). NL also recognised some of these research needs, together with the need for evaluation of the impact of a changing climate on soil biodiversity.

Regarding **soil sealing**, BE-VLG reported that there is a need for the development of regulations for an appropriate selection of soils not to be sealed and an evaluation of the impact of desealing on soil functions.

Although national databases exist in IE and FR, they identified the need for national monitoring programmes and the selection of relevant indicators for evaluating soil challenges.

Finally, FR highlighted two important aspects for knowledge development on soil degradation and soil fertility: i) the assessment of soil resilience (reflecting both the soil's tolerance to stress and the soil's ability to return to a new state of equilibrium after a disturbance); ii) science-based legislation on soil degradation and fertility.

4.2.5 General analysis across regions –soil degradation and fertility

In general, he main knowledge gaps/needs identified by the participant countries of each region are summarised in Table 5 for each soil challenge.

All the regions reported development of plenty of knowledge on factors influencing the **decline or increase of SOC** in agricultural soils. Knowledge gaps on this topic were only provided by the Northern and Southern regions. The need for quantification of the SOM status on a large scale, the definition of site-specific SOC target thresholds, and more insights on the site-specific SOM/soil structure relationship was stated by the Northern region participant countries. The Southern region for their part recognised a need for detailed monitoring and modelling of the SOC status.

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GHG emissions have been the focus of research for evaluation of the impact of different farming systems, management practices and field operations by many of the participant countries. Across regions, the need for the establishment of monitoring programmes for GHG emissions was highlighted. Additionally, the demand for quantification of GHG emissions from peatlands was reported by the Northern and Western regions, whereas the impact of agricultural practices and different agrosystems are the focus in the Southern region.

The Northern, Central and Western regions reported concern regarding **peatland degradation** and cited studies focussed on the effects of peatland degradation and restoration measurements. The need for quantification of extent of peatland and its degradation were pointed out by the participant countries of the Northern and Western regions, and the Western region raised concern about the impact of climate change on peatland degradation.

In relation to **soil structure**, the main degradation process discussed by the participant countries was soil compaction. Attention was drawn to subsoil compaction as a severe and long-lasting effect of heavy traffic on wet soils. Although comprehensive knowledge on soil compaction drivers and consequences was claimed across regions, there is a general need for an update of the national extent of subsoil compaction, more insights into its persistency and the potential impact of climate change on it. The Northern region highlighted the need for studies focussed on the development of intelligent traffic. Demands for more comprehensive studies integrating soil compaction, plant growth, water availability and yield were stated by the Northern and Western regions. The central region described the need for awareness of the effect on compaction of trampling. The Western region called for an investigation into advanced techniques for detecting soil compaction, and the Southern region identified the need for subsoil compaction/water balance assessment.

Soil erosion is a topic that has been extensively assessed in the different regions, though is of less importance in the low areas of the Northern regional countries. Therefore, monitoring programmes and modelling of erosion (water, wind and tillage) and the prevention capacity of different management practices are research needs in the Northern region. The Western region highlighted that soil erosion models need to be site-specific, and together with the Southern region sought a better understanding of the soil erosion and soil function loss relationship. The need for assessment of the impact of climate change on the different type of erosion was identified across regions.

Overall, **water storage capacity** seems to be knowledge still under development across the regions. More focus on this research topic has been established in areas with irrigation needs and salinization problems. A few knowledge gaps were provided, which are mainly the need for insights on the in-season water storage capacity at the root zone, effects of different types of drainage on water retention (Northern region) and an update on soil data needed for water storage capacity calculations (central region).

Well-established soil fertility monitoring programmes, as well as policies and regulations on fertiliser usage, seem to be, in general, the result of ample knowledge on **soil nutrient retention/use efficiency** across regions. Yet, knowledge gaps have been recognised. Some of the Northern region countries expressed the need for assessment of impact of the use of synthetic agro-inputs. In the central region, there are areas lacking fertilization scheme records and there is a need for the development of efficient site-specific fertilization methods and quantification of nutrient dynamics in different farming systems. The Western region countries called for more comprehensive soil fertility assessments, improvement of monitoring programmes and development of efficient management practices to avoid nutrient leaching. Spatial variability was considered an important factor to be included in long-term soil fertility measurements (Southern region).

Except for the Southern region, **soil contamination** was considered across the regions to be a main soil challenge. Knowledge gaps highlighted by the Northern region were monitoring programmes of

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pollutant transport and quantification of potential hazards to soil and humans. The need for monitoring programmes and studies on soil pollutant dynamics was recognised by the central region, whereas the need for analytical standards for tracing pollutants in the soil and the quantification of the extent of soil contamination were reported by the Western region countries.

Soil acidification was a concern only mentioned by the central and Western regions, where knowledge transfer on acidification impacts and quantification of derived leaching processes were the respective recognised needs. In the Central, Western and Southern regions, **soil salinization** was recognised as either a current or a potential problem. There was a general request from these regions for quantification of the extent of the salinization and estimation of the risk of increase of the affected areas under an envisaged climate change impact.

Increasing interest in **soil biodiversity** was reported across regions, yet it is a soil challenge of less focus. Nevertheless, the Northern region expressed interest in assessing the impact of soil degradation processes on soil biodiversity and the inclusion of soil biological parameter in monitoring programmes. Comprehensive studies on soil biota functionality are a research need recognised across regions. Additionally, the central region countries called for the development of methodologies for routine use, and the Western region for evaluation of the impact of climate change in soil biodiversity.

Soil sealing was a greater challenge in the Central region and these countries also reported studies on the evaluation of soil reuse for agricultural purposes after desealing. The Central region expressed the need for closer networking between sectors/with policymakers to establish a national and regional strategy for soil usage. The Central and Western regions recognised the need for awareness and assessment of the effects of soil sealing and desealing on soil functions. Regulations on soil sealing are needed in some countries of the Western region.

General knowledge gaps in soil degradation and fertility were also mentioned across regions. The Northern region requested long-term experiments involving different management practices to assess their impact on soil quality, studies on how soils and soil degradation processes are affected in different climatic zones, a national scale soil survey on parameters related to soil degradation and fertility, and the extent of soil degradation processes. The central region identified a need for improvement in knowledge exchange between researchers, farmers and advisors, and the need for long-term trials to assess the influence of different soil management practices on soil processes. The Western region recognised the need for further evaluations of the impact of climate change on soil degradation and soil fertility, the need for the development of national monitoring programmes to quantify the extent of soil challenges, the need for comprehensive studies on soil degradation and fertility challenges and their interactions, the development/introduction of simple soil quality indicators that could be applied by farmers, the implementation of knowledge exchange between scientists and farmers/advisors, and the need for a science-based policy on soil degradation. Lastly, the Southern region reported the need for long-term experiments at different scales and climatic conditions for data collection on management strategies, and the need for studies on land degradation processes and prevention measures in a changing climate

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Table 5. Knowledge gaps in soil degradation and fertility identified from the national inputs (scientific interviews and desktop review).

Soil challenges	Knowledge gaps			
	Northern Region	**Southern Region**	**Central Region**	**Western Region**
Maintain/increase SOC	• Quantification of the extent of SOM loss • Definition and establishment of site-specific SOC target thresholds • Comprehensive research on site-specific SOM decline/soil structure relationship	• Modelling and monitoring SOC at different scales and for climatic conditions		
N_2O/CH_4 emissions	• Quantification of GHG emissions from peatlands	Quantification of GHG emissions on different agroecosystems		• Comprehensive research on GHG emissions from agricultural soils and peatlands
	Across regions: • Monitoring programmes on GHG emissions			
Avoid peat degradation	• Quantification of current peatland coverage and degradation effects		• Effective knowledge transfer on peatland use impact. • Quantification of peatland degradation	• Evaluation of the impact of changing climate on peatland degradation
Optimal soil structure	• Comprehensive research on agricultural machinery effects on soil structure and plant growth • Research on soil compaction/yield effects with different soil types/climate conditions • Development of knowledge on soil compaction-intelligent traffic	• Studies on traffic effect on subsoil compaction and water balance	• Raise awareness about cattle load effects	• Comprehensive research on soil compaction effects on soil functions, crop productivity and ecosystem services under different soil type and climate conditions • Investigation on the usefulness of advanced techniques for detecting field soil compaction • Knowledge of natural resilience of compacted soils
	Across regions: • Quantification of the current extent and severity of subsoil compaction • Raise awareness of subsoil compaction and include subsoil in soil models • Evaluation of the persistency of subsoil compaction effects • Assessment of the impact of soil compaction in a changing climate • Regulations to prevent soil structure degradation			
Avoid soil erosion	• Evaluation of the impact of different agricultural systems and management practices on soil erosion • Monitoring programmes and modelling of wind, water and tillage erosion (including sediments and nutrients)	• Studies on soil erosion and soil function losses relationship		• Site-specific models on soil erosion • Effective knowledge transfer on soil erosion impact

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	Across regions: • Studies on the impact of climate change on erosion (wind, water and tillage)			
Water storage capacity	• Knowledge on water storage capacity in the root zone –in seasonal soil water dynamics. • Studies on the effect of different type of drainage on water retention		• Up-date of basic soil data for calculating water storage capacity	
Enhance soil nutrient retention/use efficiency	• Assessment of the impact of synthetic agro-inputs use in soil fertility • Monitoring programmes of different macro and micro elements	• Inclusion of spatial variability in long term soil fertility measurements	• Development of fertilisation schemes record • Definition and establishment of efficient site-specific fertilisation methods • Quantification of nutrient pathways in different farming systems	• Development of a holistic and multi-criteria approach for soil fertility assessment • Improvement of monitoring programmes • Research on how to reduce nutrient leaching under different conditions
Soil contamination	• National scale monitoring of pollutants transport to waterbodies • Quantification of potential hazards to soil and humans caused by pollutants		• Comprehensive studies on soil pollutants –dynamics and interactions • A monitoring programme for P loss	• Development of analytical standards for tracing pollutants in the soil • Quantification of the extent of soil pollutants in agricultural soils
	Across regions: • Monitoring of soil and water pollutants			
Soil acidification			• Effective knowledge transfer on soil acidification	• Quantification of the extent of leaching process on acidified soils
Soil salinization		• Monitoring programmes and modelling of soil salinization and sodification • Quantification of the current extent of salinization	• Studies on the impact of climate change on salinization risk	• Studies on the impact of climate change on salinization risk • Quantification of the current extent of salinization
Soil biodiversity	• Impact of soil degradation on soil biodiversity • Monitoring programmes of pre-defined biological parameters • Knowledge of microbial community functionality	• Knowledge of soil biota contribution to the recovery of degraded soil.	• Comprehensive studies on soil structure/soil biota/soil nutrients interactions • Development of methodologies for routine use	• Knowledge of functional diversity and the functional roles of soil biota • Impact of changing climate on soil biodiversity
	Across regions: • Comprehensive studies on soil biodiversity –functional role in ecosystem services • Standardisation of biological indicators			
Soil sealing			• Awareness of the effect of soil sealing on soil functions	• Regulations on the selection of areas to be sealed • Evaluation of the impact of desealing on soil functions

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5 Strategies for improved soil management

5.1 Review of EU and international projects and literature

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5.1.1 Introduction

In the context of agricultural production, it is crucial to maintain and improve the ability of a soil to sustain plant growth, i.e. soil fertility. This includes providing nutrients and favourable chemical, physical, and biological conditions for plant growth. Soil fertility can be promoted by safeguarding soil health, which is "the capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health" (Doran and Zeiss, 2000), as advocated by many international organisations and initiatives (Safeguarding our soils, 2017). Soil health expands the concept of soil quality, which focuses more on soil functions in relation to human needs, but the two terms largely overlap (Bunemann et al., 2018).

Many agricultural soils are exposed to degradation due to several processes, as described in the previous section of this review. It has been previously estimated that the cumulative loss of agricultural productivity in Europe due to human-induced soil degradation during the second half of the 20th century was 7.9%, but according to FAO and ITPS (2015) this was an underestimation. Degraded soils have a diminished capacity to function in a way that supports human needs and ecosystems in general. Thus, in order to promote food security, climate mitigation and provision of ecosystem services, in line with the UN Sustainable Development Goals, it is crucial to reach Land Degradation Neutrality (UNCCD) by appropriate management of agricultural soils. With this purpose in mind, many initiatives have taken place to coordinate research at international and European level (e.g., ESP, CIRCASA, INSPIRATION), and several projects have investigated best management strategies for agricultural soils.

Among others, the ongoing SoilCare project aims to "identify, test and evaluate soil-improving cropping systems (SICS) that will increase the profitability and sustainability of agriculture across Europe". Based on SoilCare´s conceptualization, soil quality can be improved by prioritizing and optimizing cropping systems, combining specific crop types and rotations and agronomic management practices. The prioritization can be based on specific soil threats (e.g., acidification, erosion and compaction) or aim at general improvement of soil conditions (e.g., soil structure and nutrition), and depends on soil type, climate, and socio-economic conditions (Oenema et al., 2017).

Across ongoing and past projects and initiatives (e.g., IPCC, GSP, SmartSOIL, RECARE, SoilCare, ClimAgri), there is agreement on the main practices that can improve (or preserve) soil quality. Namely:

- Crop diversification (species, variety) in time and space, with appropriate crop sequences;
- Permanent soil cover by using perennials, cover crops and/or leaving crop residues on the field;
- Minimum soil disturbance;
- Addition of organic amendments, such as green and animal manures;
- Water and nutrient management;
- Agroforestry

In addition, landscape management (e.g., vegetated strips), mixed farming, use of advanced technology and improved grazing have been investigated (IPBES, CIRCASA, Agforward, UNISECO, Grazing for carbon) and show potential benefits.

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The potential improvement strategies have to be considered in connection with specific conditions (pedo-climatic and socio-economic) to avoid trade-offs with other aspects such as food security and greenhouse gas emissions. Among others, SoilCare identified possible trade-offs between soil quality and short-term profitability (i.e., crop yield reduction due to widening of crop rotations and reduction of fertiliser and pesticide use) (Oenema et al., 2017), and other projects identified possible trade-offs between soil C storage and emission of N_2O (Catch-C, SmartSOIL, ResidueGas). As reported by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), benefits of sustainable land management can exceed the costs at a global level, as long as it is tailored to the specific context (IPBES 2018). The need for solutions tailored to pedo-climatic conditions and land use was also emphasised by the LANDMARK project, which aimed at developing a decision support tool (soil navigator) to provide advice on the best management options for individual farms, from both an agronomic and an ecosystem function perspective (Creamer et al., 2019). Since the effectiveness of potential improvement strategies depends on their applicability, it has been crucial to involve different stakeholders in the development of tools to support farmers and policymakers (e.g., RECARE).

Overall, the main knowledge gaps concern the effect of potential improvement strategies at different spatial and temporal scales (e.g., 4per1000, SmartSOIL, Catch-C) and possible trade-offs and synergies. In particular, it has been reported that assessing trade-offs between C input and N_2O emissions (e.g., due to residue management) requires continuous GHG emission measurements over different temporal scales and under different conditions, which is not easy to achieve. As suggested in the framework of the Catch-C project (Spiegel et al., 2014), a comprehensive assessment of potential improvement strategies should adopt an entire life cycle point of view, beyond field and farm boundaries. Knowledge of the current soil status is also crucial to assess the potential for improvement, but this requires a systematic measurement and monitoring approach, as well as the involvement of stakeholders at different levels. In this context, several projects and initiatives have reported a lack of effective monitoring strategies, with compatible measurements among countries. As suggested by the ongoing LANDSUPPORT project (EU, 2020), the lack of multi-scale support (to farmers and governments) is an obstacle for the adoption of potential soil improvement strategies (LANDSUPPORT, 2019). As highlighted by the IPCC (2019) report, there is a lack of knowledge on possible adaptation limits and potential combined effects of climate change and desertification (e.g., groundwater depletion). In addition, the impact of “freeing up” land by reducing food loss and waste for restoration/afforestation/perennialization should be investigated.

5.1.2 Strategies for improved soil management

5.1.2.1 Crop diversification

Crop diversification includes several strategies at different levels, from genetic diversification through cultivar mixtures to landscape management. Crop rotation, i.e., the succession of different crop species in the same field, is one of the most common and studied practices, with the focus being mostly on cereal and pulses (Beillouin et al., 2019). Other practices include intercropping, associated plant species (i.e., plants grown in addition to main crops, for agronomic or environmental reasons) and agroforestry.

In a meta-analysis on the effect of several strategies on SOM content, pH, aggregate stability, water-holding capacity and earthworms in long-term experiments in Europe and China, Bai et al. (2018) found that crop rotation was beneficial for earthworms, SOM and crop yield compared to monoculture. Ball et al. (2005) reviewed the effect of crop rotations (i.e., choice and sequence of crops) on soil structure and crop growth in temperate regions, highlighting how crop and soil management at different points in the rotation play a combined role. For example, alternating deep-rooted with shallow-rooted crops could help to preserve a good soil structure, reducing the need for mechanical loosening of the soil. Crop management options to improve soil structure include the use of leys, choice of crop species with diverse functional traits (e.g., root system) and continuity of crop cover. Crop management options that promote good soil structure would support the potential beneficial effects of soil management options, such as reduced soil disturbance (e.g., no tillage, controlled traffic) (Blanco-Canqui and Ruis, 2018). The input of organic matter is important for the formation of SOM, and different crops contribute differently. In particular, C and N input from belowground pools (i.e., roots and deposited in the soil) plays an essential role, as it supports microbial populations and it is more likely to be stored in the soil (Kätterer et al., 2011). The ability of different crops to form fungal associations (e.g., with arbuscolar mychorrhizal fungi) is another important aspect to consider when choosing crops to include in a rotation, as they can greatly contribute to soil structural stability and nutrient cycling (Ball et al., 2005). Studies on crop diversification in time (i.e., crop rotations) and space (i.e., intercropping) show beneficial effects in terms of soil microbial community structure and activity, related to the build-up of SOC and total N in soil microaggregates (Cong et al., 2015; Tiemann et al., 2015), which are known to be more stable (Oades, 1984).

However, studies on crop diversification under European conditions are still scarce, and the lack of a shared conceptual understanding of the term “crop diversification” complicates the generalization of results (Hufnagel et al., 2020). As pointed out by (Ball et al., 2005), the effect of diversification at the genetic level (i.e., cultivar mixtures) needs further investigation, as the contribution of different crop varieties to soil quality is not part of routine breeding programmes. Crop diversification is a relevant strategy across all environmental zones, but further research should be conducted in relation to specific crop sequences under different conditions (e.g., soil type, climate), possibly expanding the species and varieties investigated. Knowledge is still lacking about belowground pools (roots and rhizodeposits) and dynamics, as well as the spatial and temporal dynamics of C and nutrient input, emphasizing the importance of long-term studies.

5.1.2.2 Addition of organic amendments

Organic amendments include farmyard manure, compost, green manure, crop residue, slurry, digestate, biochar and organic waste. Their addition to soil increases SOM, which affects biological, chemical and physical properties, thereby influencing soil quality.

In a review on the long-term effects of organic amendments on soil quality, Diacono and Montemurro (2010) concluded that addition of organic amendments affects the abundance and activity of soil microbes, increases the content of SOC and nutrients and improves soil physical properties (e.g., water-holding capacity), mainly due to enhanced aggregate stability and reduced bulk density. However, most of these effects evolve slowly, and depend on the quantity and quality of the added material, as well as the management. In this regard, soil disturbance (e.g., tillage) influences the turnover of the added material and the persistence over time (Lal, 2007), as well as the abundance of earthworms and other soil biota, which is generally increased by addition of organic material (Bai et al., 2018). In addition, organic amendments can be beneficial for the remediation of soils affected by excessive salinity and/or sodicity, due to the increased cation exchange capacity, the effect on pH, and the improved soil physical properties favouring infiltration and passage of water (Leogrande and Vitti, 2019) and also reducing the risk of erosion. However, optimal rates of application should be identified to reduce possible drawbacks, such as accumulation of soluble salts, leaching of nutrients and emissions of GHG. Timing and method of application of the organic amendments are important factors to consider, as they affect availability and potential loss of nutrients as well as soil physical and biological properties, through the use of heavy machinery (Schröder et al., 2018).

Even though it is often assumed that input of organic material correlates linearly with a build-up of SOC (Bais-Moleman et al., 2019) and an increase in soil quality, changes in management (Powlson et al., 2008), soil initial status and clay content (Jensen et al., 2019), relative distribution of C between different soil fractions (Cotrufo et al., 2019) and environmental conditions have to be taken into account. Use of biochar is considered as a promising strategy for SOC sequestration, being composed of approximately 90% C in a relatively stable form. Depending on the characteristics of the starting material, biochar can improve soil physical and chemical properties, such as soil water retention and availability of some nutrients. However, research on biochar is still in its early stage, and the importance of starting material and processing method in determining the effect of biochar calls for standard requirements for distribution (Schröder et al., 2018).

Input of organic materials has been proven crucial for improving soil quality. However, the emerging understanding suggests that the formation and stabilization of SOM are mediated by microbial anabolism, and thus it is not driven by the decomposition and transformation of organic matter *per se* (Liang et al., 2017). In this regard, there is still a considerable lack of knowledge on the dynamics controlling these processes in the short and long term. Soil functional complexity has recently been suggested as a key concept to understanding SOC sequestration, which should guide soil management strategies to manipulate the balance between C inputs and losses (Lehmann et al., 2020). However, soil management strategies should vary among locations, since the effect of organic amendments on SOC and soil quality is influenced by soil initial conditions and changes and environmental conditions. Thus, it is crucial to take into account the influence of different environmental zones and management strategies, on which knowledge is still lacking.

5.1.2.3 Permanent soil cover (perennials, cover crops)

Leaving the soil bare during periods that are not suitable for crop production (e.g., autumn and winter in Northern Europe) and between crop rows, exacerbates the risk of erosion by wind and water, which is one of the main soil degradation processes in Europe. Permanent soil cover is crucial for protecting the soil across all environmental zones, and can be achieved by using perennials, cover crops and/or leaving crop residues on the field (Jones et al., 2012).

Several factors contribute to the reduction in soil loss thanks to a permanent soil cover, such as increased surface roughness, reduced sealing, increased infiltration capacity and improved soil chemical and physical properties. Permanent soil cover through the use of perennials can be achieved by implementing beneficial land-use change (LUC), i.e., converting areas under annual crops to perennial grasses, woody plants or innovative perennial cereals (Duchene et al., 2019; Englund et al., 2020). As suggested by Englund et al. (2020), in a high-resolution land-use modelling study across EU28, strategic perennialization of areas at risk of soil degradation and with high mitigation potential would be a viable and effective strategy. The adoption of perennials should be based on local conditions (including landscape characteristics) and priorities, and does not necessarily entail the conversion of entire fields (e.g., riparian buffer zones and wind breaks). Compared to annual crops, perennials generally lead to an increase in SOC, due to a greater input of organic matter and reduced soil disturbance, but the effect varies based on the context and the initial conditions. On the downside, conversion of areas from annual to perennial crops could result in production losses, which could be offset by biorefining the biomass produced into a variety of products, including animal feed, depending on available technology and infrastructure (Englund et al., 2020). Using cover crops is another valuable option to maintain a constant soil cover, which does not require LUC. Cover crops are grown during periods that are not suitable for normal crop production and between crop rows, to provide soil protection and enhance nutrient management. The potential of cover crops to provide multiple ecosystem services is widely recognised, and include: reduction in nitrate leaching, reduction in soil salinization, increase in SOM, improvement of soil structure (e.g., aggregate stability, porosity, water retention) and fertility, increase in macro-faunal activity and reduction in soil erosion (Daryanto et al., 2018; Fageria et al., 2005). In addition, cover crops have been shown to enhance microbial biomass and activity, which are key to nutrient cycling and SOC sequestration, as well as to improving soil structure (Liang et al., 2017).

To optimise the provision of ecosystem services from cover crops, the right species have to be selected, mixed and periodically rotated, which requires further investigations. Agronomic characteristics (e.g., establishment, winter hardiness, biomass production), root structure, ability to fix N_2, competitiveness for resources and quality of residues are some of the aspects that should be considered in order to target the specific context (Fageria et al., 2005). One of the main potential trade-offs and lack of knowledge is the contribution of cover crops to SOC storage and N_2O emissions, which relates to the quantity and quality of

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organic inputs (residues and deposits) and management (i.e., tillage), and is affected by the specific conditions (e.g., soil type and status, climate) (Quemada et al., 2020).

5.1.2.4 Reduced soil disturbance

No-Tillage (NT) (also known as “zero tillage” or “direct drilling”) refers to land cultivation without soil inversion, limiting soil disturbance to a minimum and with direct drilling of seeds. The absence of ploughing and harrowing aims to promote soil health, enhancing soil structure and biodiversity and, possibly, to reduce GHG emissions.

Overall, NT can increase soil aggregate stability, SOM content in the upper soil layer and earthworm populations compared to conventional tillage (Bai et al., 2018). In a review of the literature on NT in Northern, Western and South-western Europe, Soane et al. (2012) identified the advantages and disadvantages of NT from an agronomic and environmental point of view. Relative to conventional tillage (mouldboard ploughing), NT reduces soil compaction, reduces erosion and runoff, offers the possibility to grow cover crops or autumn-sown crops and enhances soil micro- and macro-fauna (i.e., mychorrizal fungi, earthworms). Keeping the crop residues on the soil surface can increase the SOM content in the topsoil, but its feasibility depends on soil type, amount and type of residues and climatic conditions. In particular, direct drilling of cereal crops in crop residues can be troublesome in Northern Europe, due to the soil being too wet and a reduced fraction of solar radiation reaching the soil, which could be an advantage in drier regions. This is reflected in greater crop yields under NT compared to conventional till in Southern Europe, while the opposite is reported for Northern Europe. In addition, soil type plays a crucial role for the success of NT, and soils with poor drainage and weak structure were found to be unsuitable for NT (Soane et al., 2012).

Besides the possible lower yields, the higher soil moisture and greater C and N contents in the topsoil can lead to greater N_2O emissions under NT compared to ploughing. This is a possible trade-off to be taken into account, especially in Northern Europe, even though several factors interact to determine N dynamics in the soil. In organic cropping systems, the use of NT could exacerbate problems with weeds, which are mainly controlled mechanically. In the same way, cover crop termination represents a challenge for organic farmers both in Northern and Southern Europe, and the use of frost-sensitive varieties or living mulches carries other drawbacks that need to be considered (Vincent-Caboud et al., 2017).

Among the main research needs is the effect of time. As some effects of NT are visible only after years (VandenBygaart et al., 1999), ideally studies should take into account a perspective of at least three years and possibly more. The time frame is important also in relation to N_2O emissions, as a slow improvement of soil structure could reduce the negative effect on N_2O in the long term. In addition, there is still a lack of knowledge on the interacting effect of several factors (e.g., soil type, C and N status, temperature) on GHG emissions, especially N_2O but also CO_2, as well as C sequestration potential (Soane et al., 2012). For the latter, the mechanisms controlling soil C sequestration and long-term storage are not fully understood yet. Further research is also needed on the effect of NT under different crop rotations, as the selection of crop types and sequence is crucial for a complete assessment of NT. Especially in the context of organic agriculture (but not only), there is a lack of knowledge on cover crop management and weed control, with the choice of cover crop species being a crucial point (Vincent-Caboud et al., 2017). Finally, Soane et al. (2012) suggested that “a European wide classification of the suitability of soils for no-till should be considered”.

5.1.2.5 Water and nutrient management

Water management is a key strategy for dealing with soil erosion and salinization, which is caused by an imbalance between water inputs and transpiration in combination with poor drainage, causing an accumulation of water-soluble salts near the soil surface. This is a critical issue along the Mediterranean coastline, and can be ameliorated by adopting water management practices that prevent waterlogging and temporal over-irrigation, which is also crucial in preventing erosion and surface runoff (Cuevas et al., 2019).

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In a review of soil-improving cropping systems for soil salinization, Cuevas et al. (2019) report that leaching of water through the soil profile, accompanied by efficient drainage, is the main strategy to prevent salinization, but excessive leaching can lead to nutrient losses. Water management practices such as micro-irrigation and deficit irrigation can be effective in dealing with soil salinity by reducing the rise of the water table, even though leaching of water through the soil may be reduced. In addition, optimised fertilization programmes should limit a surplus of fertiliser salts, preventing further salinization.

In a broader perspective, nutrient management affects soil quality indirectly by influencing crop growth and hence plant-soil dynamics, and directly by influencing the microbial community and, in the case of organic amendments, by adding OM to the soil. In particular, nutrient availability has been shown to be critical for C sequestration in agricultural soils, mainly due to its effect on microbial anabolism (Kirkby et al., 2014; Liang et al., 2017). Therefore, nutrient management is critical not only to support crop production, but also to sustain soil health.

Since the current understanding of the dynamics controlling SOC storage is evolving (Cotrufo et al., 2019), there is still a considerable lack of knowledge on the optimal management of nutrients, which should be targeted the specific conditions and soil status (including the distribution of SOM in pools of mineral-associated versus particulate organic matter).

5.1.2.6 Agroforestry

Agroforestry entails the integration of woody vegetation in arable and/or livestock systems to obtain beneficial ecological and economic interactions. In Europe, agroforestry has been largely abandoned during the 20th century, but it has gained new interest for its positive environmental effects (Nerlich et al., 2013). In a meta-analysis aimed at analysing the effect of agroforestry in different European regions, Torralba et al. (2016) found that it is effective at controlling soil erosion, reducing surface-runoff and enhancing soil fertility, with an increase in SOM and nutrients in soil. This was particularly relevant in areas prone to drought stress, such as in the Mediterranean region, where most of the studies were concentrated. Results regarding the effect of agroforestry on provisioning services (e.g., biomass and food production) were highly variable, indicating that benefits of agroforestry are related to the specific context, and highlighting the relevance of combining different elements in the system. For example, possible reductions in yield could be avoided by combining agroforestry with specific crop rotations aimed at a complementary use of resources (Beillouin et al., 2019).

An overall assessment of the potential of agroforestry to improve soil conditions is limited by most of the studies being focussed in areas prone to high temperatures and drought stress. In addition, an evaluation of trade-offs and synergies with the provision of other ecosystem services (e.g., biodiversity) requires that different scales are taken into account, as some of the effects of agroforestry are more pronounced at landscape- than at farm-scale (Torralba et al., 2016).

5.1.2.7 Advanced technology and other future farming strategies

Since the 1990s, the use of advanced technology to characterise differences within arable fields has been an important step towards a more efficient use of resources. Today´s emerging technologies include mobile proximal sensors and drones, which will help to overcome some of the limitations of remote-sensing systems, such as satellites, in mapping soil quality and detecting variability within fields (Schröder et al., 2018). This will allow the adoption of targeted management measures, aimed at improving and preserving soil quality and health.

The impact of grazing in organic and conventional mixed farms on soil quality indicators was recently investigated in northern England by Zani et al. (2020), who found an increase in available nutrients (specifically phosphorus), soil C and microbial C in the topsoil, as well as positive effects on soil physical properties as compared to systems without grazing. The observed effects could be associated with the impact of grazing animals on biomass production, plant species composition in leys, resource allocation and availability of easily degradable OM to the microbial community, potentially promoting long-term storage of SOC. However, grazing intensity should be carefully considered and studies under different pedo-climatic conditions are scarce. In addition, possible trade-offs with GHG emissions from grazing ruminants could counterbalance the effect on SOC sequestration, and deserve further investigation.

In cases of soil contamination (e.g., with metal(loid)s or persistent organic chemicals), phytoremediation can be a valuable option to reduce existing or potential risks and to restore soil health. Phytoremediation consists of using living plants or plant-microbe associations to remove, degrade, sequester, volatilize or stabilize contaminants. Plant biomass can then be used for other purposes than food and feed, such as biorefinery and energy production (Schröder et al., 2018).

5.1.3 Overall summary

An overview of the knowledge gaps identified based on the review of European and international projects and literature for each potential improvement strategy can be seen in Table 1.

Table 6. Overview of knowledge gaps for potential improvement strategies.

Strategies for improved soil management	**Knowledge gaps**
Crop diversification	• Effect of diversification at the genetic level (i.e., cultivar mixtures). • Specific crop sequences under different conditions (e.g., soil type, climate). • Belowground pools (roots and rhizodeposits) and dynamics. • Root:shoot ratio of crops and the contribution of crop residues to soil organic matter. • Spatial and temporal dynamics of C and nutrient input (importance of long-term studies). • Lack of a shared conceptual understanding of the term "crop diversification".
Addition of organic amendments	• Dynamics controlling the effect of organic amendments on soil quality in the short- and long-term, specifically focusing on the role of soil microbes. • Comprehensive assessment of the effect of management, changes in management and initial conditions (including relative distribution of C between different soil fractions). • Requirements for distribution of biochar, considering the effect of starting material for biochar production and processing method.
Permanent soil cover	• Assessment of the "perennialization potential" at local scale across Europe. • Selection of species and varieties to optimise the provision of multiple ecosystem services. • Selection and management of cover crops to limit possible trade-offs (e.g., N_2O emissions), including periodic rotation and taking into account specific conditions and temporal scale.

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Reduced soil disturbance	• Long-term perspective, also in relation to N_2O emissions. • Interaction of several factors (e.g., soil type, C and N status, temperature) on C sequestration potential and GHG emissions. • Mechanism controlling soil C sequestration and long-term storage. • Effect of NT under different crop rotations (crop types and sequence). • Cover crop management and weed control (especially relevant in organic agriculture), with the choice of cover crop species being a crucial point.
Water and nutrient management	• Optimal management of water and nutrients targeted the specific conditions and soil status (including the distribution of SOM in pools of mineral-associated versus particulate organic matter).
Agroforestry	• Overall assessment of the potential of agroforestry to improve soil conditions in Europe. • Evaluation of trade-offs and synergies with the provision of other ecosystem services (e.g., biodiversity) at different scales, and especially at landscape-scale.
Other	• Effect of grazing and grazing intensity on soil quality under different pedo-climatic conditions.

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5.2 Synthesis of national inputs

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The strategies for improved soil management synthesis involves the state-of-the-art knowledge and the knowledge gaps highlighted by the country members of EJP SOIL. The synthesis is structured according to the four main European regions defined in section 1.1 of this report (Figure 4).

5.2.1 Northern region

The following synthesis is based on NO, DK, FI, LV, SE and LT inputs. EE did not submit their contribution to this report in time.

The main farm management categories reported across countries in this region are agricultural systems, crops/crop rotation, organic matter and nutrient management, and tillage and traffic. Water management was a common concern for DK, FI and LT, and crop protection for LT.

Regarding SOC decline, the main strategies applied in DK are crop rotation and organic manure. **Organic resource** measures are also generally used in NO; however, NO expressed concern on the effect of long-distance transportation on the quality of organic resources. Long-term experiments in NO have shown that less intensive agricultural practices (e.g., reduced tillage) may not increase total SOC storage, though redistribution of C might occur in the soil profile. Individual studies showed that SOC stocks might increase when having initial, low SOC concentrations, but the SOC-sink potential is limited in systems such as permanent grasslands with high SOC stocks. NO reported that there is limited information on the management of alpine grasslands/rangelands. In NO, environmentally friendly organic manure spreading rates are granted at national scale to reduce N and P leaching, GHG emissions and the odour associated with spreading. LT highlighted the need for monitoring programmes on soil C, chemical and physical properties to help stakeholders make the right decisions concerning soil sustainability. FI considered that the fertiliser recommendation could be updated to include micronutrients. Additionally, FI recognised the need for studies on the potential use of sediment from lakes/seas/wetlands as fertiliser.

Control of **peat degradation** in DK is by rewetting of peat soils. DK reported a need for monitoring of depletion rate of peatlands and evaluation of the effect of rewetting on GHG emissions.

In LT, there is increasing interest in the adoption of direct seeding, no-till and reduced **tillage**. Research in long-term experiments has shown the relation between no-till and C sequestration being soil texture-dependent (LT). However, LT recognised that there is a lack of agreement on the effect of soil tillage on soil structure formation, C sequestration and CO_2 emissions, and the influence of soil texture on their relationships. There is therefore significant scientific interest in research on long-term no-till effects on soil properties on different soil types, and on how long reduced and no-till may be applied on the same place according to soil type and texture. Direct seeding or conservation agriculture is practised in SE on less than 10% of the agricultural area, whereas mouldboard ploughing is implemented in about 70% of the agricultural area.

NO research has shown that minimum tillage combined with drier soil reduced stress occurrences in the upper soil, and that lighter mechanization favour a good seedbed under excess soil moisture conditions. In DK, NO and SE the decision-making tool ‘Terranimo’ is used to assist farmers’ decision-making regarding field **traffic**. Although tyre type and pressure impact on **soil compaction** is well known in DK and NO, Terranimo is reported not to be generally applied. DK pointed out the need for the development of lightweight autonomous robots for field operations, and decision support tools for route planning, as well as studies on

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field readiness assessment. NO mentioned that controlled traffic farming is of increasing interest in the country, but there are currently no grants available for these practices. In DK, controlled traffic farming is not widely adopted because its implementation is expensive and may require heavier machinery. DK calls for a policy on reporting planned field traffic prior to commencing fieldwork.

DK and SE further call for a stronger focus on the long-term persistency of **subsoil compaction**. Knowledge of the use of biological subsoilers is a potential management strategy that has been studied in DK and is a research need in FI. However, as, pointed out by NO, there is a need to quantify the contribution of deep-rooted **crops** on soil properties (SOC content in deeper layers) with plants suitable for local conditions. FI also pointed out that studies on soil resilience are needed to ensure sustainable agronomic functionality, and also called for further emphasis on subsoil compaction studies. SE mentioned that on-field studies are essential for goal-oriented cooperation with farmers and knowledge transfer.

NO had several studies on evaluation of practices for **soil erosion** control – including modelling. Erosion risk maps are in place in NO and are used for implementing measures (e.g., reduced tillage and spring tillage) and subsidy levels for reducing erosion in agriculture. The adoption of reduced tillage in NO varies greatly between years. In DK, water erosion mitigation measures (winter cereals, cover crops and no-tillage in autumn) are side benefits of policies addressing soil fertility issues. There is a limited public programme supporting the establishment of riparian buffer zones in DK – these are mainly voluntary establishments. Therefore, in DK there is a need for: i) more specific research on conservation practices to avoid soil erosion, ii) development of a prediction tool for tillage erosion risk based on different scenarios, and iii) establishment of prevention policies.

Although there are well-known positive effects of crop residues and reduced tillage on **water management**, SOM and nutrient supply, long-term experiments at the farm level in LT revealed varying effects on SOC accumulation and soil water retention. Research in DK has been conducted on the use of biochar to increase soil water retention and root development; other studies have focussed on the use of sensors for in-situ root monitoring and the estimation of soil water deficit. In a climate change perspective, there is a strong need for more studies on drought-resistant crops and management strategies under Nordic-Baltic conditions. The use of biochar in NO focussed on C-sequestration strategies for policy measures, yet the production of biochar in NO is limited. Similarly, FI stated that management practices that favour the accumulation of SOC could also increase water storage capacity.

In the Nordic-Baltic countries, legislation commonly stipulates the use of **catch/cover crops** and **crop rotation** practices to reduce N-leaching. As a side effect, these management practices are recognised as favouring soil structure and biodiversity. DK reported a need to investigate the **plant mixtures/soil biodiversity** relationship under different scenarios to understand their potential roles in integrated **soil fertility** management. The main farm management strategies applied to improve soil biodiversity in DK are grasslands, cover crops and crop mixtures. NO also recognised soil fauna as a key factor in soil health (soil structure and protection of SOC); hence, individual studies on soil biota have been conducted in the country. In SE, legislation on ecological focus areas has led to an increase in fallow areas and the use of cover crops in regions vulnerable to N leaching.

LV stated that soil use is a topic currently integrated into environmental, agricultural, energy and climate policies. Land management law in LV requires soil mapping and land quality assessment to be carried out at least every 20 years, though is it not practised. Further knowledge availability and gaps were not provided in the input by LV.

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5.2.2 Southern region

The common farm management categories reported in the Southern region are agricultural systems, tillage and traffic. Buffer strips and crops/crop rotation were considered by ES, IT and TR. Organic matter and nutrient management were a concern for ES and TR, crop protection for IT and water management for PT.

Multiple crop rotation systems were reported to attain an increase in SOC and N in IT, especially in organically managed vegetable production systems and rotations with large residue inputs. Agricultural systems with combined management practices have been found to be effective in the reduction of GHGs in central PT, e.g., studies conducted in a double-cropping system with band incorporation of acidified raw slurry.

Crop rotations are common for rainfed winter cereal cropping in ES, where studies have shown the positive effects of this practice on C stock, prevention of soil erosion and runoff, soil fertility, soil structure, soil cover and weed control. **Intercropping and perennial crops** are other improved management strategies successfully used in IT. Perennial crops such as orchards, olive groves and vineyards are of importance in the Mediterranean area and, depending on the management strategy, have a positive influence on SOC and N, which favours climate change mitigation. Oak trees in PT, for example, increased soil moisture and reduced GHG emission. PT noted the need for long-term experiments on soil management and climate change under these systems. ES reported the implementation of legume-rich Dehesas mixtures, an agro-silvopastoral system with cork or holm oak identical to Montado in PT, with positive effects on pasture yield and soil nutrient balance.

Studies in southern IT have shown that the use of **cover crops** in vineyards reduced soil erosion and increased SOC, and when different sequences of cover crops are used in orange plantations there was an increase in soil N and P depending on cover crop sequence. IT also pointed out that the beneficial effect of cover crops extends to soil structure stability and soil biodiversity in addition to SOC stock and GHG emissions, yet it varies depending on tillage system and cover crop type. PT mentioned that using a combination of green manure of mixed cover crops and composts increased crop yields over time. PT stated the need for further studies on the contribution of organic fertilisers to SOM in agricultural soils. ES reported up to 50% reductions in soil erosion in orchards and vineyards following the use of cover crops, and pointed out soil structure, reduced water and N losses, weed control, pollinator attraction, and soil fauna diversity as positive effects.

In IT, there is a research focus on the use of biodegradable **mulch** instead of plastic film in order to reduce plastic waste. In IT, research has also demonstrated the efficacy of grass strips, resulting in a fivefold reduction in erosion. The usage of pruning residues to reduce water evaporation and runoff was mentioned by ES and the need to study how much time they may last on the soil surface to enable a possible expansion to larger areas. No further information on the research needs was provided in relation to buffer strip use in the inputs from the Southern region.

Within **tillage and traffic** management strategies, no-till was pointed out by IT as a management practice increasingly adopted. Studies have shown that under Mediterranean conditions (IT, ES), no-till increased soil water infiltration/retention, SOM, and soil biodiversity, and reduced N runoff, N leaching and fossil fuel consumption for soil work. Reduced tillage and no-till were also observed to contribute to a GHG emission reduction, a boost in microbial biomass and activity, and an increase in crop yield (ES). In PT, however, no-till is reported to decrease or to not have a consistent impact on the yield of wheat and maize in the first years of adoption. Countries from this region did not report a research need in relation to tillage and traffic.

Regarding **water management** in this region, ES reported using irrigation in all agricultural areas of the country, by using different irrigation systems according to the conditions. Research in ES showed that ultra-low flow discharge emitters and a high frequency of irrigation effectively reduce nutrient leaching. Water use efficiency has also been demonstrated by using irrigation systems such as subsurface drip irrigation and smart irrigation scheduling, as well as management strategies such as partial root-zone drying strategies and partial

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or entire irrigation reduction. Although much research has been conducted on this topic, ES indicated the need to study the relation between growth stages and water restrictions for different crops, as well as the need to perform more holistic studies on water and nitrogen use efficiency.

Water-holding capacity was reported to increase when using organic fertilisers in degraded Portuguese vineyards soils, which was directly associated with an increase in the quality of clusters/vine and yield. Modelling work in PT found sorghum to be a drought-resistant crop and moderately tolerant of saline water. However, the country recognised the need for calibration and validation of modelling methodologies for relevant soil processes. In PT, there is increasing knowledge of water management and agricultural systems management. Yet, there is a lack of knowledge on universal methodologies for soil-crop-water model calibration, monitoring programmes for collection of soil hydraulic property data, and measures to mitigate climate change impact with a focus on irrigation implementation.

The use of **organic fertilisers** in ES was reported to increase SOC and SOC stock, at a greater rate under irrigation than under rainfed in conventional systems, especially when compost was used and horticulture implemented. Organic farming, however, showed a varying effect on SOC and N stocks, depending on soil type (ES). Decision support systems for **fertilization** are implemented in ES, especially in areas vulnerable to nitrate contamination. ES also highlighted positive effects of using biofertiliser (biostimulants, nitrogen-fixing microorganisms, mycorrhizae) on plant nutrient content and productivity. In addition, several studies in PT have shown the contribution of organic amendments to P-use efficiency, pH correction, use of saline water and GHG emissions. However, monitoring and modelling from long-term field experiments are needed to evaluate the potential of amendments – including biochar – on soil C stock.

PT further emphasised the extended research work conducted on the application of organic fertilisers to agricultural soils in the country. Regarding **soil biodiversity**, the use of composted olive by-products in PT has improved the ryegrass mycorrhizal association and crop yield, although no effect was found on N and P supply. In southern PT, it was found that alternative slurry application techniques compared to raw slurry injection led to similar effects on soil properties, but had no effect on enzymatic activity. Studies conducted in PT found that the species sensitivity distribution is a potential ecotoxicological indicator for safe use of organic fertilisers in agricultural soils and could be evaluated for use in the national regulations. PT recognised the need for studies on the contribution of microorganisms to soil productivity and the importance of soil microbiota for the development of sustainable soil management practices.

PT additionally listed as general knowledge gaps the need to integrate soil variability in modelling; to evaluate the functionality of soil maps in terms of modelling; to have open databases on soils, climate and management practices to better define policies to counteract soil degradation; to focus on prediction of soil erosion; and to study the impacts of climate change on soil functions in the Mediterranean regions. PT also highlighted the need for more comprehensive studies on the implementation of different management practices and their effects on soil functions under different scenarios of soil type, agricultural system, and scale.

TR focussed its report on the national structure for research request/application implementation, which is summarised as follows Application of policies on sustainable soil and land management - in line with international developments - is currently ongoing on a national scale. A national and multi-institutional Consultative Committee of Agricultural Research was created in TR to annually collect the national requests related to agricultural research, in order to plan research subjects according to the priorities of the country. Yet, TR realised the need for improvement in the capacities of all the institutions working in soil science.

ES pointed out that the implementation of these soil management practices demands their adaptation to specific local and regional conditions, and their consideration in integrated rural planning.

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5.2.3 Central region

The most common farm management categories reported in the Central region are organic matter and nutrient management, tillage and traffic, agricultural systems and crops/crop rotation. Across the countries, management practices have been investigated individually (with long term experiments as a valuable infrastructure), whereas interactions between management practices have hardly been studied. This knowledge of interactions would be needed for practical advice for farmers. New technologies and soil management methods should be tested under realistic conditions, e.g., on demonstration farms as suggested by HU. There is still a need to study precision agriculture and the use of advanced technologies in large-scale farming (CZ).

Research projects in CZ have focussed on the effects of **farming systems,** and it was shown that conventional systems led to a decrease in nutrient cycling processes (lower enzyme activities) and a decline in soil quality and C sequestration compared to organic farming systems. AT, SI and DE all had studies on crop rotation and catch/cover crops. AT stated that a diverse **crop rotation** contributes to nutrient use efficiency and to climate change adaptation. In DE, research on optimizing crop rotations, including catch crops, to reduce GHG emissions and soil erosion and to increase water and nutrient efficiency is ongoing. PL reported that currently there is no reliable data on crop rotation at a national scale, but a national census for this is planned for autumn 2020.

Regarding **increasing SOC**, AT identified the following management practices as effective: optimization of crop rotation, catch/cover crops, organic fertiliser application, organic farming, biochar application and reduced tillage / no-till (only in the topsoil). The increased SOC content, in turn, has positive effects on soil structure and water retention. As for grassland, SK and AT identified a knowledge deficiency on the impact of various grassland management systems on the SOM content and the C cycle in pastures. CZ reported that management practices aiming at maximizing hay production (liming and fertilization) were found to reduce belowground C storage by 20% in grassland (CZ). In PL, straw and manure are the two most common practices implemented. In this country, there is a need for regulations on the use of compost and solid digestates.

There is a repeatedly mentioned need to study the efficient use of organic amendments and the effects of different processing techniques (with a life-cycle assessment) on GHG emissions and nutrient leaching (DE, CH, and SI). Alongside, DE expressed the need to evaluate the different pathways of competing biomass use (food, feed, fibre, C sequestration) and their related ecosystem functions.

A decrease in **GHG emissions** could be found with reduced and no-till management practices (CH, CZ), by replacing mineral fertilisers with organic sources and by using composted farmyard manure instead of manure-based slurries. Moreover, increasing the proportion of clover in the grass-clover mixture promotes biological nitrogen fixation and reduces fertiliser input (CH), although there is still some uncertainty related to the impacts of practices aiming to reduce GHG emissions on crop yields, especially under a changing climate, which should be identified on a regional scale (CH).

Peatlands were mentioned as a contentious topic in CH since there is currently no economically viable option of peatland restoration. Additional options and policy instruments are therefore deemed necessary to protect the remaining peatlands.

Reduced / non-inversion tillage was reported to attain a significant decrease in soil erosion rates in several countries (CH, CZ, AT). Reduced tillage and no-till lead to an accumulation of SOC and nutrients in the topsoil layer and increase biotic activity and water retention (AT). Since conservation tillage requires suitable soil conditions, it is necessary to determine where this is beneficial and where these practices are problematic (CZ). Conservation tillage systems (SI) and the evaluation of environmentally friendly weed control measures as alternatives to ploughing (AT) were stated as research needs. In PL, an increasing interest in strip-till practice has been identified by stakeholders, though there is no knowledge on the extent of no-till.

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Swiss erosion risk maps and soil compaction risk maps identify areas prone to **erosion** and **soil compaction**, respectively, and therefore support farmers and local authorities in taking appropriate measures. Despite this framework, both the implementation of policies and farmers' access to information about soil erosion were stated to need improvement. As for soil compaction, recommendations on tyre pressure and construction as well as online soil moisture data are available to support decisions for agricultural and construction-related soil management (CH). While in AT the research on crops prone to erosion is ongoing, CZ has identified shallow strip-tillage before sowing and an adaptation of row width as effective measures in maize cultivation. The topics of soil structure and compaction seem to leave uncertainties and requirements for further investigation. A holistic concept to avoid soil compaction and to improve soil structure is still missing (AT). For farmers, a need for simple methods to assess soil structural quality was identified by CH, and a link between compaction risk assessment and machine control software. Soil and water protection schemes are sectorial implemented in PL in areas susceptible to erosion, with low SOC or nitrogen vulnerable zones.

Similarly, several countries stated the need for further research regarding **water storage capacity** and **water management**. Increasing the soil's humus content can enhance water availability and resistance to extreme weather events (AT). However, CZ mentioned a lack of knowledge on improving the infiltration and water-holding capacity in intensive agriculture and on the use of drainage systems for irrigation and water retention. Ideally, the result will be an integrated concept to support water storage capacity (AT).

In CH, the Swiss Soil Strategy lists measures and directions to counteract soil challenges, and the Soil Protection Ordinance secures **soil fertility** through monitoring, soil protection and remediation. SI is undertaking amendments to the soil and fertilization monitoring chapter in The Agriculture Act, and a Strategic Plan addressing soils and additional laws (e.g., Decree on Fertilisers and Fertilization) are being prepared. In AT, a comprehensive environmental law does not exist, but a large number of recommendations and guidelines are available. SI also reported gaps in their legislation, which does not cover all important goals and measures needed for better soil fertility management.

Even though management practices promoting **biodiversity** (reduced or no-tillage, incorporation of cover crops, use of organic fertilisers and organic farming) are well known, many of these practices are not economically feasible for farmers. Therefore, more information regarding economically profitable, targeted and site-specific practices is needed (CH).

Soil sealing was mentioned as a largely unsolved challenge in CH and AT. There is a strong need for a strategy to protect valuable soils (AT). In addition, the potential and prerequisites for unsealing and restoring soils require more research, particularly the soil's potential to provide ecosystem services after restoration (CH).

In general, a strong, frequently stated need in the central region is the monitoring of (alternative) soil management practices and the investigation of their short- and long-term effects on soil parameters, soil quality and climate change resilience (HU, CH, AT). These studies should ideally fulfil the demands of both science and agricultural practice and be incorporated into an extensive database (DE). Knowledge on the extent of implementation of non-compulsory management practices is a general need highlighted by PL.

Evidence-based tools to assess and recommend site-specific soil management need to be developed with holistic approaches (including plant nutrition and crop protection). Digital tools for site-specific fertilization would be desirable for farmers and authorities (CH). SK has a system to identify a soil's suitability for the cultivation of specific crops, which is available to farmers, and AT has a standard on soil function.

Another important aspect is the assessment of farmers' motives and constraints regarding the implementation of sustainable management practices (DE). Social barriers regarding the implementation of soil protection measures need to be better understood (CH), and strategies for encouraging/motivating farmers to adopt sustainable practices are required (DE).

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Green direct payments (from the state and the EU) supporting sustainable soil management practices would enable the transition to more sustainable agricultural practices but are currently missing in SK. CH supports the direct payment scheme for motivating farmers to adopt effective management practices that reduce GHG emissions, yet the scheme requires optimization. The Austrian programme for environmentally friendly agriculture (ÖPUL) promotes sustainable management practices through financial support in order to reduce GHG emissions, erosion, nutrient loss, etc., and is widely accepted.

HU assessed the approach of the EU Mission Board for Soil Health and Food and did not provide comprehensive information on national knowledge availability and knowledge gaps. Poland did not submit any report.

5.2.4 Western region

The main farm management categories reported across countries in this region are agricultural systems, crops/crop rotation, organic matter and nutrient management, and tillage and traffic. IE and BE-WAL additionally identified buffer strips, small landscape elements and crop protection, whereas water management was a concern for IE and NL.

Within the Western region inputs, FR reported that much of the knowledge on strategies for improved soil management is based on single experiments on management practices and that local results are commonly extrapolated to other zones. They pointed out the need for addressing a more complex combination of soil management practices under different conditions within FR and suggested taking into account spatial heterogeneity as part of the management. In this region, common management practices under current adoption and ongoing research were identified for IE and the UK.

In the Western region, grasslands are of importance within the agricultural systems. In IE, grasslands occupy 93% of the agricultural area and are characterised by organic manure inputs, even during winter as organic manure is stored and then recycled back to the grassland soils. In IE the most common soil protection grassland management practices are: on-off grazing when soils are wet, yearly traffic tracks alternation, high application rates of C in organic manures to compacted areas, extended use of nutrient management plan based on the EU Nitrates Directive, growing multispecies and deep-rooting swards, inclusion of clover legumes (N input) when re-seeding grassland, and soil pH correction. The UK also reports the latter three practices to be beneficial and to contribute to increasing C and N stocks in soils, to improve soil nutrient use efficiency and soil biological health.

The contribution of different organic resources – and their decomposition rates – to the SOC stock has been the focus of several studies in NL and BE-VLG. Additionally, BE-VLG also mentioned the evaluation of ecosystem services provided by SOC and the relation between SOC and soil water availability as a research need.

Irish farmers typically improve SOM content by straw incorporation, farmyard manure or mushroom compost application (considering N and P limits), organic fertiliser application, use of cover crops/green cover in autumn combined with spring crops, including grass in the crop rotation cycle, reduced tillage, and returning the land to permanent pasture when SOM is very low. The majority of these practices were also recognised by the UK as beneficial for multiple soil challenges as they have a positive impact on biogeochemical properties.

The use of cover crops is an extended practice in IE and UK, although the benefits may be limited due to the short length of the growing season for cover crops in these countries. In the UK, cover crops have been shown to contribute to maintaining/increasing soil C stocks by reducing soil erosion and nutrient losses from soils. BE-VLG mentioned that cover crops and (temporary) grassland contribute to enhanced nutrient use efficiency and stimulated N mineralization, respectively, but crop rotation, in general, was stated to be understudied

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in BE-VLG. IE specified the need for more research related to the use of cover crops on a different texture and cropping history, and the assessment of the agronomy of cover crop species. IE and NL also stated the need to study crop rotations and cover crop effects on SOM and the impact on productivity and soil quality.

In BE-WAL, companion plants (mixture crops) have been studied elaborately and shown to improve soil biodiversity, control weed infestation, increase soil organic C and N content and may provide a host plant with arbuscular mycorrhiza fungi. However, the optimal factors for companion plants as well as the evidence for the effects of organic farming on soil quality lack in BE-WAL.

Measures to improve soil structure include reduced tillage, controlled traffic farming, reduced machine load (subsoil), low pressure in tyres (topsoil), strip cultivation, grass-clover mixtures and central and flexible tyre inflation systems (still under development) (NL). In IE, direct seeding or minimum tillage are used for re-seeding of grasslands to preserve soil structural quality and reduce C loss. Although reduced soil tillage frequency in the UK has been shown to maintain/increase soil C stocks across agroecosystems, more in-depth studies on the effect of soil tillage frequency (and re-seeding) on soil C stocks in grasslands are needed. This statement is based on the output of studies conducted in the last decade in the UK showing that no-till contributes to increasing soil C accumulation, but no clear differences were observed between conservation tillage and conventional tillage in agricultural grasslands.

BE-VLG reported that the use of non-inversion tillage decreased soil erosion rates, improved nutrient utilization by crops and reduced acidification risk and nutrient leaching. NL stated that reduced tillage causes nutrient stratification with a high SOM concentration in the topsoil, but the effect on the total C stock has not been fully elucidated. In addition, the effects of reduced tillage on natural soil processes and ecosystem services are not sufficiently known (NL). The UK highlighted the need to control farming traffic to reduce soil disturbance and soil compaction. The UK also emphasised the need for organic agricultural practices and agroecological approaches combined with precision agriculture to improve soil ecosystem functioning.

It is known that water storage capacity and availability are improved through a healthy soil structure, which also increases the soil's resilience to extreme weather events. In addition, organic matter application can enhance water availability, whereas this does not buffer extreme precipitation (NL). BE-VLG reported the need to investigate factors determining water-holding capacity and to develop strategies to create optimal water management under a changing climate. BE-VLG additionally reported ongoing research on irrigation management and potential limited availability of natural water resources in the near future. IE reported the current execution of farm-level measures and other measures to protect and enhance water quality.

Regarding crop protection, IE was the only country of the region to mention the use of a pest control approach that prioritises cultural, physical and biological aspects.

Soil fertility in IE comprises institutional farm-level measures and other measures implemented to, directly and indirectly, protect and enhance water quality by meeting Ireland's obligations. Measures concerning the safe application of fertiliser (either organic or chemical) are common practices on Irish farms to avoid water body pollution associated with agricultural soils, e.g., fixed threshold for manure and slurry spreading, a timetable for spreading of fertiliser, maximum fertilization rates based on crop requirements, buffer strip use, wintergreen cover, non-spreading buffers in the vicinity of drinking water abstraction points, minimum production of sediments, and keeping records of farm activities. BE-VLG has ongoing research on precision fertilization with slurry to predict N availability for crops, as well as efficient fertilization investigation and monitoring programmes in horticulture.

BE-VLG conducted many studies on organic fertilisers, especially (farm) compost, and found positive effects on soil quality upon repeated compost application but inconsistent effects on crop yield. The effects of biochar and biochar-compost on soil quality have also been investigated by BE-VLG. Detailed knowledge and practical decision tools are required to select the most suitable strategies for organic material (based on the whole life cycle), including advanced understanding of the trade-off between GHG emissions and SOC increase (BE-VLG, NL). Moreover, the long-term soil fertility of organic farms having little or no access to farmyard manure is uncertain (BE-WAL). In BE-VLG, the effect of crop residues on soil nutrient status and water dynamics has been reported in a few studies.

Both UK and NL reported that controlled subsurface drainage is an effective measure to avoid peatland degradation. Although this practice also maintains productive farming systems in peatlands, it increases the demand for water (NL). Thus, the effect of subsurface drains on the water table levels and on the water quality should be investigated (UK and NL).

The use of hedgerows was mentioned by IE and BE-VLG, who reported (ongoing) research on the role of hedgerows from a water quality, biodiversity and climate regulation perspective. Ongoing research on agroforestry and its impact on soil water management, biodiversity and soil fertility was reported by BE-VLG.

Regarding biodiversity, BE-VLG identified the need to conduct research on the interrelations between soil microbiology, soil structure and C cycling. The NL mentioned the development of measures to increase soil resilience to pests and diseases as necessary.

FR and IE identified the need for further tools to support integrated decision-making related to soil management and the translation of scientific research into practical recommendations for farmers. In this regard, FR suggested the development of multiple management strategies for farmer selection and adaptation in their fields. Additionally, FR reported the need for science-based management practices/strategies that should undergo cost-benefit analysis before being introduced to farmers. FR identified the need for a more holistic approach in soil management practices taking into account farmers' knowledge, for example: i) development of comprehensive approaches for soil management including the empirical knowledge of farmers/advisors and different scenarios of soil/climate and socioeconomic conditions, and ii) definition of criteria for the selection of incentives to promote soil management practices, that could take into account local constraints.

The UK, for its part, mentioned that a new Environmental Land Management policy scheme would be applied from 2024, which includes avoidance of cultivating/trafficking on wet soils, increasing SOM content, maintaining water levels in peat soils, contour ploughing, minimum- or no-tillage cultivation, sub-soiling and maize management, and creation of low intervention water pathway management techniques.

Western region countries identified the need for soil monitoring and data on (alternative) soil management practices and the investigation of effects on soil parameters (BE-VLG, BE-WAL, FR, NL). This should also include trade-offs between cropping systems and soil functions under different conditions (soil type, climate, farming system) (BE-WAL, NL).

For this region, FR focussed on the knowledge gaps within the country, and no report on knowledge availability was provided.

5.2.5 General analysis across regions –Strategies for improved soil management

From the above synthesis of the national inputs on strategies for improved soil management – knowledge availability and knowledge gaps - it is evident that the seven **Farm Management Categories** listed in the EJP SOIL guidelines are of relevance and under application in the participant countries. Table 7 displays the knowledge gaps/needs identified by the participant countries for each Farm Management Category. **Buffer strips/small landscape elements** and **crop protection** were pointed out as main Farm Management Categories by a few countries, although the information provided on the knowledge availability was very limited, and no knowledge gap provided.

Across regions, research has been conducted to evaluate the impact of different **agricultural systems** on SOM and nutrient dynamics. Yet, comprehensive studies that integrate different crops, soil properties, soil type,

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climate conditions and various management practices were not reported. On the other hand, all the regions described the existence of several studies on **cover crops, crop mixtures and crop rotations**. In this regard, the regions recognised the need for evaluating crop species that could be used in rotation or mixture to recover degraded soil structure (Northern region), increase SOM content and site-specific suitability (Western region), and adapt to a changing climate (Southern region).

There is a general interest in the use of **organic fertilisers** and amendments among the participant countries. Knowledge on this topic is diverse, in correspondence with the agro-climatic conditions and legislations of each country/region. However, a common concern is a need for more comprehensive studies of the site-specific effect of organic inputs on **SOC storage** and soil quality/fertility – using different local organic resources. Regional knowledge gaps reported are: i) Northern region: assessment of SOC storage in grasslands/rangelands and monitoring of SOC related properties; ii) central region: evaluation of grassland and peatland management and SOM dynamics, interrelations between organic inputs, GHG emissions and nutrient losses, and improvement of soil fertility management regulations; iii) Western region: time span of the effects of management practices on SOC storage, productivity, water availability, and soil quality; iv) Southern region: impact of organic amendments on SOC storage; v) trade-offs between GHG emissions and SOC increase.

Heavy machinery and traffic on wet soil were generally recognised as the main cause of soil compaction across regions. Hence, research has focussed on the use of less intense **tillage** and other field operations. Yet, across regions, there is a need for more insight into site-specific effects of reduced tillage and no-till under different (scenarios of) soil type, crop and climate. Additionally, there is a general need for evaluation of site-specific subsoil compaction mitigation strategies. The Northern and Western regions highlighted the need for further studies on the use of controlled traffic farming and precision agriculture. Assessing the potential of conservation tillage to prevent soil structure degradation is a common research need in the Northern and central regions. The Nordic countries identified the need for the development of less heavy machinery/lightweight autonomous robots for field operations in order to reduce the risk of soil compaction.

In a changing climate, the four regions recognised the need for comprehensive studies on site-specific management strategies for efficient **water management**. Regional needs are emphasised in the selection of drought-resistant crops and management strategies (Northern region), insights into water-holding capacity under different conditions (Central and Western regions), and studies on the relationship between growth stage and water restrictions under different scenarios (Southern region).

General gaps in relation to a broad sustainable soil management scheme were also expressed by each region. As summarised in Table 7, monitoring programmes for soil parameters (indicators) in combination with management practices (site-specific and climate change scenario approaches) are required across regions. Cost-effectiveness and applicability of soil-improving practices, as well as the knowledge transfer from scientific research to practical recommendations for farmers, were also highlighted as key gaps to achieve climate-smart sustainable soil management. Finally, although regulation exists to fulfil agroecological principles, an effort is still needed to develop science-based policy decisions.

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Table 7. Knowledge gaps in strategies for improved soil management identified from the national inputs (scientific interviews and desktop review).

Farm management categories	**Knowledge gaps**			
	Northern Region	**Southern Region**	**Central Region**	**Western Region**
Agricultural systems	• Assessment of potential management strategies for sustainable monoculture systems		• Studies on precision agriculture and the use of advanced technologies • Interactions between management practices	• Evaluation of complex combination of soil management practices under different conditions/systems
Buffer strips and small landscape elements	• Not directly addressed in any national report			
Crops/crop rotations	• Assessments of deep-rooted crops as potential bio-subsoilers • Evaluation of cover crops mixtures, bio-residue and biochar effects on soil structure • Evaluation of crop mixtures, their favourable link to soil biodiversity and their potential for integrated soil fertility management	• Comprehensive studies on soil management and climate change under intercropping and perennial systems		• Studies on the effect of crop rotations, including catch/cover crops, on SOM and soil quality • Multidisciplinary studies on the use of cover crops under different soil type and cropping history • Evaluation of the optimal factors for companion plants
Organic matter and nutrient management	• Assessment of SOC storage in grasslands/rangelands • Monitoring programme on SOC and its related chemical and physical properties • Assessment of the potential use of sediment from lakes/seas/wetlands as fertiliser	• Monitoring and modelling from long-term field experiments to evaluate the potential of amendments –including biochar– on soil C stock	• Evaluation of the impact of different grassland management systems on the SOM content and the C cycle. • Assessment of the effects of different organic amendments on GHG emissions and nutrient losses • Evaluation of different practices for peatland restoration • Improve soil fertility management regulations	• Evaluation of short- and long-term effects of combined soil management practices on SOC stock and productivity • Comprehensive studies on SOC and water availability relationship • Development of decision tools to select suitable strategies for the use of organic sources • Comprehensive assessment of the impact of organic farming on soil quality
	Across regions • Comprehensive studies on the effect of different organic resources (fertilisers and amendments) on SOC storage and soil quality/fertility			
Tillage and traffic	• Studies on the use of controlled traffic farming and its effects on soil structure • Development of less heavy machinery/lightweight autonomous robots for field operations • Quantification of drainage and tillage effects on peatlands • Studies focussed on conservational tillage to avoid soil erosion		• Development of a holistic concept to improve soil structure and avoid soil compaction • Assessment of alternative weed-controlling measures under conservation tillage • Assessment of soil structural quality and the link between compaction risk assessment and machine control software	• Comprehensive studies on the type of tillage and frequency effects on grasslands • Holistic approach to alleviate soil compaction • Investigation on the use of controlled traffic farming and precision agriculture in agroecological approaches

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	Across regions • Assessment of management practices to mitigate subsoil compaction • Comprehensive studies on site-specific effects of reduced tillage and no-till on soil processes/properties and ecosystem services			
Crop protection	Not directly addressed in any national report			
Water management	• Studies on drought-resistant crops and management strategies under Nordic-Baltic conditions	• Studies with a focus on irrigation implementation in a changing climate • Comprehensive studies on relationship between growth stage and water restrictions for different crops and soil type – monitoring programmes and model calibration • Studies focussed on water- and N-use efficiency relationships under varying crop management conditions	• Develop a holistic concept to improve soil water availability	• Investigate factors determining water-holding capacity under different soil type and farming systems • Studies focussed on water level control and water quality in peatlands
	Across regions • Comprehensive studies on management practices for efficient water management (site-specific) under a changing climate			
General gaps	• Development of management strategies to avoid soil compaction • Science-based policy on soil erosion control and soil structure degradation – incentives	• Studies focussed on soil microbiota activity/composition and contribution to soil health • Comprehensive studies on integrated crop systems and soil management practices at different scales • Studies on the impact of climate change on soil functions and measures to mitigate the impact	• Develop tools for site-specific management recommendations • Assessment of cost-effectiveness and applicability of soil-improving practices and (social) constraints in implementation by farmers • Evaluation of different management practices under climate change scenarios • Find economically profitable and site-specific practices that promote soil biodiversity • Science-based policy to protect vulnerable areas –peatlands • Investigate unsealing and soil's potential after restoration	• Development of integrated decision-making tools related to soil management -translation of scientific research into practical recommendations for farmers • Assessment of cost-effectiveness of management practices/strategies before being introduced to the farmer • Definition of criteria for the selection of incentives to promote soil management practices –local scale
	Across regions • Monitoring programmes of different soil parameters to be used for soil sustainable management decisions • Monitoring and modelling sustainable soil management practices at a site-specific level under a climate change scenario			

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6 Summary and Conclusion

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This report reviews available knowledge within the members of the EJP SOIL consortium and in EU projects and literature. This section synthesise across reviews of European projects and literature and 24 national inputs. Especially, the latter differed in quality, level of details and specific focus. We do not, however, expect this to have significantly influenced the overall analysis and conclusions given that many countries contributed to the work and that the analysis was also based on an overall review of EU projects and literature.

We addressed three topics: Carbon stock, Soil degradation and fertility and Strategies for improved soil management, which cover the EJP Soil challenges and Land management categories shown in Figure 1. The topics are strongly connected, and so are the extracted knowledge gaps. To illustrate the strong functional linkage between knowledge gaps for the three topics, we will take offset in the two 'Carbon stock' knowledge gaps from the national inputs that were expressed by all regions, i.e., Deep soil carbon and its dynamics, and Impacts of deep roots on C stocks (Figure 8). Firstly, the two knowledge gaps are strongly interlinked, as deep roots contribute to deep soil carbon. Secondly, deep soil carbon and deep roots are linked to knowledge related to other soil challenges – e.g., knowledge gaps in relation to enhanced nutrient retention, increased water storage capacity and mitigation of subsoil compaction. Lastly, deep soil carbon and deep roots link to knowledge gaps for 'Strategies for improved soil management' on the development of new cropping systems, which include deep-rooted crops – as a single crop or in mixtures.

Some strong functional linkages can be drawn between knowledge gaps for all three topics. However, there are also examples where strong linkages can only be made between knowledge gaps for 'Strategies for improved soil management' and either 'Soil degradation and fertility' or 'Carbon stock'. For instance, knowledge gaps on pollutants and their dynamics in soil are linked with knowledge gaps on developing management strategies to limit problems with pollutants. Knowledge gaps on pollutants and their dynamics are, however, not necessarily related to knowledge gaps on 'Carbon stock'.

In the following three sections, we start with ´Carbon stock´ and synthesise the different inputs from literature research, projects, initiatives and organisations as well as national enquiries. In the final section, we follow up on the interlinkages and overlaps within the three topics in order to draw conclusions from this report.

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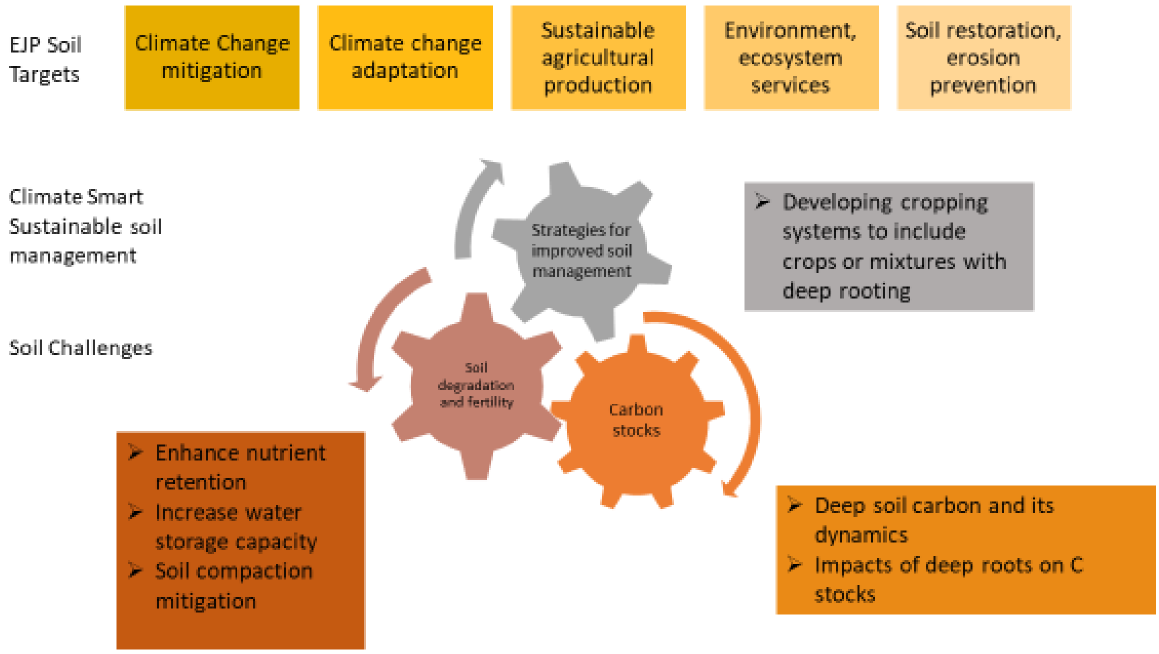

Figure 8. Example illustrating strong linkage between knowledge gaps expressed for the topics addressed in this report: Carbon stock, Soil degradation and fertility and Strategies for improved soil management.

6.1 Carbon stock

This section summarises knowledge gaps regarding carbon stocks described in the review of EU projects and literature (Table 2) and in the national inputs (Table 3 and Figure 7).

6.1.1 Knowledge gaps for topics in common identified from the review of EU projects and literature and of national inputs

The analysis of European literature identified several knowledge gaps on carbon stocks, which were also expressed in the national inputs. Starting with the topic of management practices for carbon, the **assessment and mapping of SOC under various management practices** and **life cycle assessment of management options** beyond farm-scale were stated**.** The effect of C enhancing management measures on **GHG emissions** is another aspect that deserves close attention.

Regarding the assessment and **quantification of SOC**, the need for **standardised approaches** across nations was reported in European literature and national inputs. Moreover, a common research gap was found on the topic of **deep soil carbon** and the influence of management and environmental factors on it. **SOC spatial and temporal dynamics** as well as accounting for **historic land use and SOC distribution** are further knowledge needs expressed at the level of national inputs and European literature. Insufficient information on **SOC sequestration potentials** of different soils across Europe was another central issue. **Monitoring of SOC changes** in long-term field experiments and assessing their uncertainties are other challenges mentioned both in the European literature and national inputs.

Concerning knowledge gaps from a farm perspective, credible, low-cost **tools to determine SOC stocks for farmers** are sought. Knowledge on soil policy, in particular on the **impacts of policies on C**

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sequestration and **the transfer of information** to relevant stakeholders, is requested within European literature and national inputs.

Both European and national data analysis found that there is a lack in **mapping peatlands and estimating their SOC stocks**. Identification of peat thickness and carbon contents are essential steps that are often missing. Knowledge gaps aligned across the review of European projects and literature, and national reports are shown in Figure 9.

6.1.2 Knowledge gaps specific to the review of European projects and literature.

The European-wide analysis of projects and literature revealed several knowledge gaps. Firstly, a **scarcity of studies on other land categories** such as mountains, bare ground, urban areas and lynchets was identified. The **costs and benefits** of various management practices should be assessed when quantifying their potentials**.** The analysis of the European literature also found knowledge gaps on **biophysical and biochemical interactions or erosion** and their effects on SOC. Several programmes and projects at the European level stated a **need for novel techniques to assess SOC** as well as **expanded databases**. The **influence of the changing climate and land use on SOC** was listed as research needs in the literature. In this context, the **reversibility of C sequestration** under climate change and uncertainties regarding the **effectiveness of C sequestering management practices** were mentioned.

6.1.3 Knowledge gaps specific to the national inputs.

When looking at the national inputs and synthesised knowledge gaps at a European regional level, several topics, which were specific to these inputs and were not mentioned in the European literature review, could be identified. Most importantly, **deep roots and their impacts on SOC stocks** need to be acknowledged, as this research need was found in all four regions. Further, the potentials of **organic wastes as agricultural amendments** should be discussed in the future. Insufficient monitoring and the need for a **common monitoring system** was mentioned in three of the four regions. Lastly, improved **modelling of SOC** was identified as a knowledge gap.

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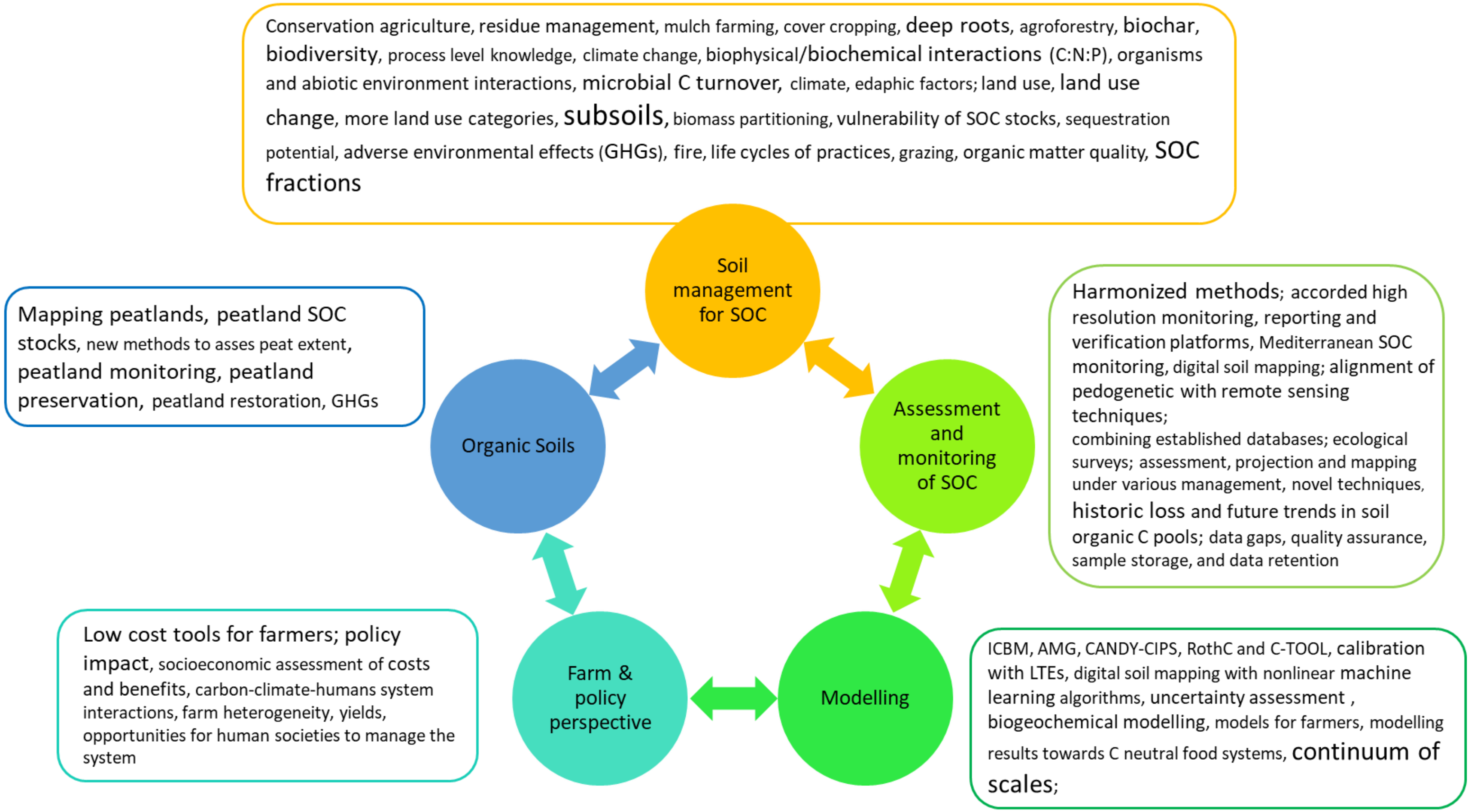

Figure 9. Knowledge gaps on carbon stocks aligned and assembled according to the topics. Sources are (i) literature research, (ii) projects, initiatives and organisations and (iii) national enquiries. Size of letters indicates in a descending order how often the knowledge gap was mentioned. List may not be exhaustive and wording was adjusted according to meaning.

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6.2 Soil degradation and fertility

This section summarises knowledge gaps regarding soil degradation and fertility (Figure 10) from the review of EU projects and literature (Table 4) and described in national inputs (Table 5).

6.2.1 Knowledge gaps for topics in common identified from the review of EU projects and literature and of national inputs

Maintain/increase SOC. Knowledge gaps on modelling and monitoring changes in SOC at different scales and climates and the link between SOC and soil structure are expressed in the national inputs and in the review of EU projects and literature. The latter includes knowledge gaps focusing more strongly on methodology and mechanistic understanding – reporting knowledge gaps on soil mineral SOC interaction in relation to soil structure, productivity and soil nutrients, and improved techniques to study the fate of SOM in soils. See also knowledge gaps on Carbon stock (5.1).

Optimal soil structure. There is a need for more knowledge on the impact of field traffic, livestock trampling and management practices on soil structure, soil functions and plant growth in different pedo-climatic zones; more thorough assessment of the state of soil compaction in Europe and the usefulness of advanced methods for detecting soil compaction; and development of engineering solutions to limit the risk of compaction (e.g., lightweight robots, intelligent traffic). Knowledge gaps on the persistence and natural resilience of compacted soils was highlighted in the national inputs. The review of European projects and literature stressed the research gaps on improved mechanistic understanding of the soil compaction process and that more knowledge is needed on the influence of soil compaction on GHG emissions. Assessment of soil compaction impact in a changing climate and regulation measures to prevent soil structure degradation was mentioned as knowledge gaps in the national inputs.

Avoid soil erosion. Improved monitoring programmes for wind, water and tillage erosion were stressed as an important knowledge gap. This included development/implementation/harmonization of technologies for sampling with high temporal and spatial resolution, harmonization of erosion rate data, and common database systems for data storage. Knowledge gaps on modelling of soil erosion and impacts of soil erosion (sediment and nutrient loss) were highlighted. This included development of site-specific models and improved validation of the models. The review of European projects and literature expressed a need for a deeper understanding of the soil erosion mechanisms and the consideration of all erosion types when estimating erosion rates. It also stressed the need to study economic incentives for farmers to conserve the soil resource for future generations.

Avoid soil contamination. There is a lack of monitoring programmes and harmonised monitoring systems for pollutants in member countries and at European scale. A need for standards for collection, analysis and tracing of pollution was also stressed. More attention to the behaviour and dynamics of pollutants in soils is also needed. Optimizing the use of plants for remediation of contaminated soils and the need for long-term soil remediation experiments were mentioned as knowledge gaps in the review of EU projects and literature. The impact and fate of emerging contaminants (pharmaceuticals etc.) were also stressed as a knowledge gap in the latter.

Avoid soil salinization. There is a need to develop monitoring programmes of soil salinization in Europe by, for example, satellite imagery. A need for studies on the impact of climate change on salinization risk was stressed in the national inputs. Improved understanding of C dynamics in saline soils and the need for developing improved crop, soil and water management in soils at risk of salinization was emphasised as knowledge gaps in the review of European projects and literature.

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Avoid soil sealing. Development of standard procedures for quantifying soil sealing is needed according to the review of European projects and literature. The national inputs mention knowledge gaps on the evaluation of the impact of soil sealing and the need to develop regulations on soil sealing.

Avoid soil acidification. The review of EU projects and literature mention the lack of systematic monitoring data for non-forest soils as a knowledge gap. The national inputs mention increased insight into the impact of increased NOx and NH_3 input – acting as acidifying agents - and the influence of acidity on leaching processes as knowledge gaps.

6.2.2 Knowledge gaps for topics specific to the review of European projects and literature

Desertification. Lack of a standard methodology to assess desertification in Europe and lack of data on the risk of desertification (drought vulnerability, climate change) were stated as knowledge gaps. There is also a need for improved insight into the use and interpretation of desertification data collected in Europe. There is also a lack of knowledge on the impact of drought mitigation measures.

6.2.3 Knowledge gaps for topics specific to the national inputs

Avoid N_2O/CH_4 emission. The national inputs stress knowledge gaps on the quantification of emissions from peatlands and different agroecosystems and the need for monitoring programmes.

Avoid peat degradation. National inputs highlight knowledge gaps on quantification of peatland cover and degradation and impact of peatland use and the influence of climate change on peat degradation.

Enhance water storage capacity. The knowledge gaps mentioned in the national inputs are the lack of up-to-date basic soil data to calculate water storage capacity and insufficient knowledge on water storage capacity at root zone level (taking into account rooting depths).

Enhance soil biodiversity. Development of monitoring programmes and standard analysis methodology was stated as knowledge gaps. Lack of knowledge on the interaction between soil biodiversity and soil degradation and soil health was stressed. Further, knowledge gaps on functional diversity, functional role of soil biota, and the interaction between soil structure, nutrients and biota were also mentioned.

Enhance soil nutrient retention/use efficiency. A wide range of knowledge gaps were stated in the national inputs (Table 5) from development of fertilization schemes over increased insight into methods to reduce nutrient leaching to development of a holistic and multi-criteria approach for soil fertility assessment.

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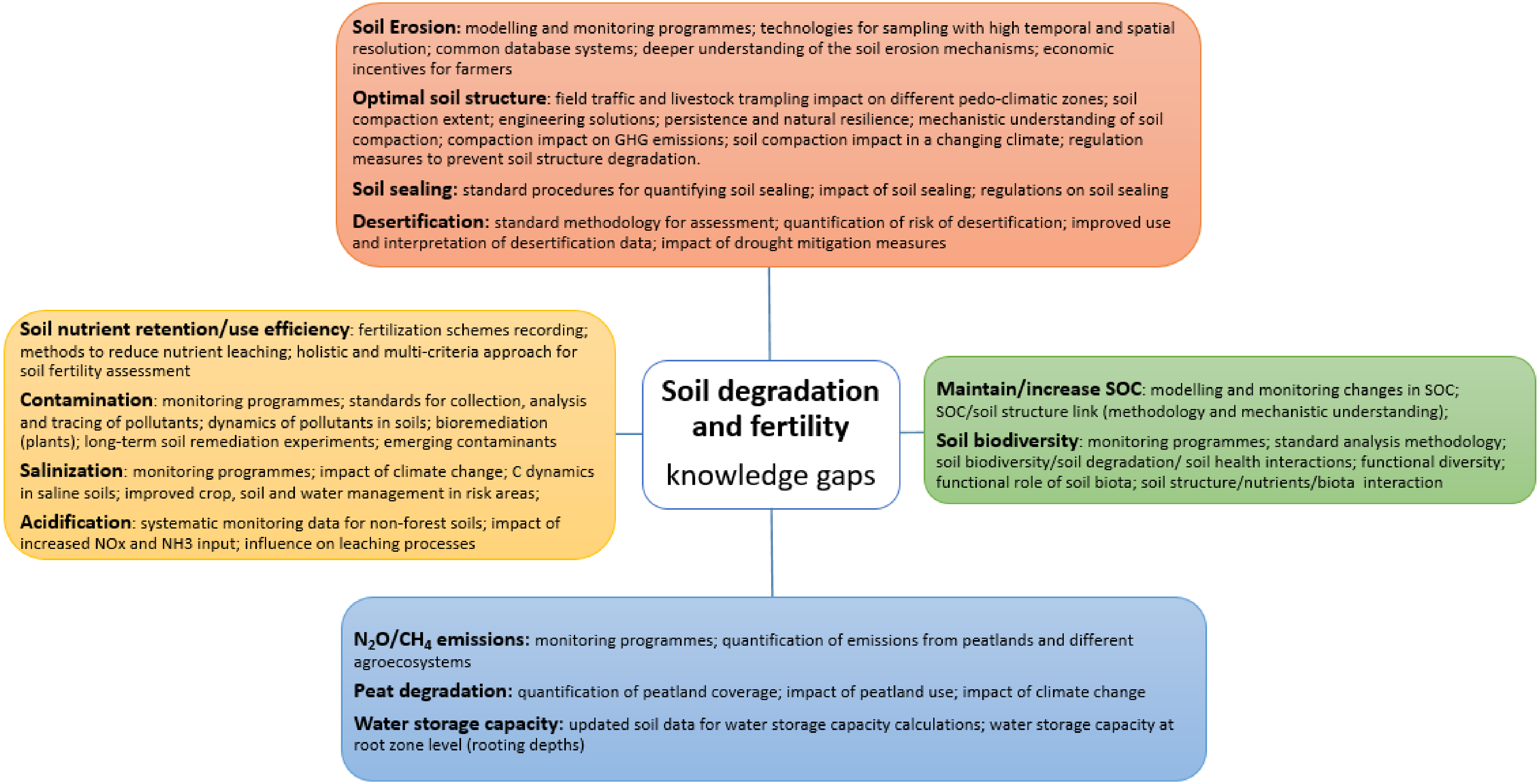

Figure 10. Summary of knowledge gaps on soil degradation and fertility from the review of EU projects and literature and described in national inputs.

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6.3 Strategies for improved soil management

This section summarises knowledge gaps regarding strategies for improved soil management (Figure 11) from the review of EU projects (Table 6) and described in literature and national inputs (Table 7).

6.3.1 Common knowledge gaps from the review of national inputs and EU projects and literature

Organic matter and nutrient management. The review of EU projects and literature focussed on improved mechanistic understanding of the impact of organic amendments (spatio-temporal dynamics, interaction with soil microbes, distribution of C input between soil fractions) and including the starting material for biochar production and processing when assessing requirements for the distribution of biochar. The national inputs focus on knowledge gaps on grassland management in relation to C storage and cycling, and assessment of the effect of different organic amendments (manure, crop residues, biochar etc.) on soil C storage, GHG emissions, productivity, nutrient losses, water availability and soil quality. There was, across regions, a call for comprehensive studies on the effect of organic resources on soil C storage and soil quality and fertility. Development of decision support tools for optimizing the use of organic resources was also mentioned as a need.

Crops/crop rotations. At system level, the review of EU projects and literature described knowledge gaps on crop diversification - from a need for a common conceptual understanding of the term to effects of diversification at cultivar and genetic level on spatial and temporal dynamics of C and nutrients in the soil-plant-atmosphere system. For perennial cropping, knowledge gaps include the need for studies on the potential of perennialization, and on optimization to provide multiple ecosystem services (e.g., limit trade-offs of C sequestration on, e.g., N_2O emissions). The national inputs focus strongly on gaps on cover crops, cover crop mixtures, deep-rooted crops and intercropping as a mean to achieve multiple benefits (soil biodiversity, improved fertility and soil quality, C storage, etc.). There was a call for multidisciplinary/comprehensive studies of cover cropping, intercropping and perennial cropping under different pedo-climatic conditions and with consideration of climate change.

Tillage and traffic. The knowledge gaps stated in the review of EU projects and literature focussed on the need for improved mechanistic understanding of tillage effects on C storage, N_2O emissions and the interaction of several factors including soil type, C and N status and temperature. In the synthesis of the national inputs, two knowledge gaps were stated across regions: 1. Comprehensive studies on the effects of reduced tillage and no-tillage on soil processes/properties and ecosystem services, and 2. assessment of management practices to mitigate subsoil compaction. Regional inputs include more detailed gaps regarding #1, i.e., the need for studies on conservation tillage effects on soil erosion, weed control in relation to grassland and peatland management. The national inputs also included more specific gaps in relation to soil compaction such as a need for studies on controlled traffic farming and development of lightweight field robots.

6.3.2 Knowledge gaps for topics specific to the review of European projects and literature

Agroforestry. The main knowledge gaps addressed in the review of EU projects and literature were summarised as a need for: 1. Assessment of the potential of agroforestry as a soil improving cropping system in Europe, 2. Evaluation of trade-offs and synergies with the provision of other ecosystem services at different spatial scales.

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6.3.3 Knowledge gaps for topics specific to the national inputs

Agricultural systems. Two general gaps were synthesised across regions: 1. Monitoring programmes for different soil parameters to be used for soil sustainable management decisions, 2. Monitoring and modelling of sustainable soil management practices at a site-specific level under different climate change scenarios. The need for developing site-specific/precision agriculture practices and recommendations was also expressed. Further, a number of inputs highlighted the need for studies on the cost-effectiveness and applicability of soil improving practices seen from a farmer's (socio-economic) point of view. Other inputs focussed on the need for studies on developing science-based policy for soil protection.

Water management. The synthesis of the national inputs stated, across regions, a need for comprehensive studies on management practices for efficient water management (site-specific) in a changing climate. This was supplemented with knowledge gaps (expressed in different regions) on developing holistic concepts for system/modelling studies on management strategies, factors affecting water-holding capacity for different soils/farming systems to more specific needs for studies on drought-resistant crops, growth stage / water restriction relationship for different crops and soils. A need for studies on improved water management in peatlands was also expressed.

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Strategies for improved soil management

Knowledge gaps

Agricultural systems:
- Monitoring programmes for sustainable management decisions
- Monitoring and modelling at a site-specific level (climate change scenarios)
- Site-specific/precision agriculture practices

Agroforestry:
- Benefits of agroforestry as a soil improving cropping system
- Trade-offs and synergies with the provision of other ecosystem services at different spatial scales

Crops/crop rotations:
- Crop diversification
- Diversification at cultivar and genetic level on spatial and temporal dynamics of C and nutrients
- Potential of perennialization
- Optimization of multiple ecosystem services
- Cover crops/cover crop mixtures/deep-rooted crops /intercropping benefits
- Multidisciplinary /comprehensive studies under different pedo-climatic conditions and climate change scenarios

Organic matter and nutrients management:
- Impact of organic amendments
- Starting material /processing for biochar production and distribution
- C storage and cycling in grasslands
- Edaphic and environmental effect of organic amendments
- Effect of organic resources on soil C storage, soil quality and fertility
- Decision support tools for organic resources use optimization

Tillage and traffic:
- Tillage effects on C storage
- Impact on N_2O emissions
- Soil type /C/N/temperature interaction
- Reduced tillage /no-tillage on soil processes/properties and ecosystem services
- Practices to mitigate subsoil compaction
- Conservation tillage effects in grasslands and peatlands
- Controlled traffic farming; lightweight field robots

Water management:
- Efficient water management (site-specific) in changing climate
- System/modelling studies on management strategies
- Factors affecting water holding capacity (site/system-specific)
- Drought-resistant crops
- Stage-water restriction relationship for different crops and soils
- Water management in peatlands

Figure 11. Summary of knowledge gaps on strategies for improved soil management from the review of EU projects and literature and described in national inputs.

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6.4 Overarching knowledge gaps across the three topics and Conclusions

In the introduction to this summary, we highlight the functional linkages between the different topics 'Carbon stock', 'Soil degradation and fertility' and/or 'Strategies for improved soil management'. In addition to these functional linkages we found some issues of special concern recurring in the individual reports on these topics. These issues are displayed in Figure 12 and the knowledge gaps collected within these issues can be seen in Table 8 in Appendix B. For instance, **peatlands** were mentioned for all topics. They are of concern both for their large carbon stocks, as an endangered habitat affected by degradation, and peatland restoration and management is a matter for potential improvement strategies. **Models and monitoring** are overarching issues as they constitute important tools, which are needed to tackle problems on all topics. A further issue that recurred in all three topics is **soil compaction**, which demands improved management, as it affects C stocks and results in soil degradation.

When interpreting these results, it has to be kept in mind that overlapping issues and highlighted knowledge gaps of the national inputs, also reflect the way questions were asked in the interviews. However, it shows that for some matters a predominant need for information is expressed by European soil experts. The positive conclusion from this report is that the majority of knowledge gaps mentioned by national experts have been envisaged within the proposal and the roadmap of the EJP soil. For example, the need for **harmonised soil data** and aligned **monitoring** programmes already receives major attention as an entire work package (WP6) in the EJP soil framework programme is devoted to this matter. Nonetheless, this report will help to prioritise research according to the raised knowledge gaps. It may also help to include some important aspects and specific research questions listed in the tables herein, which now can receive special attention.

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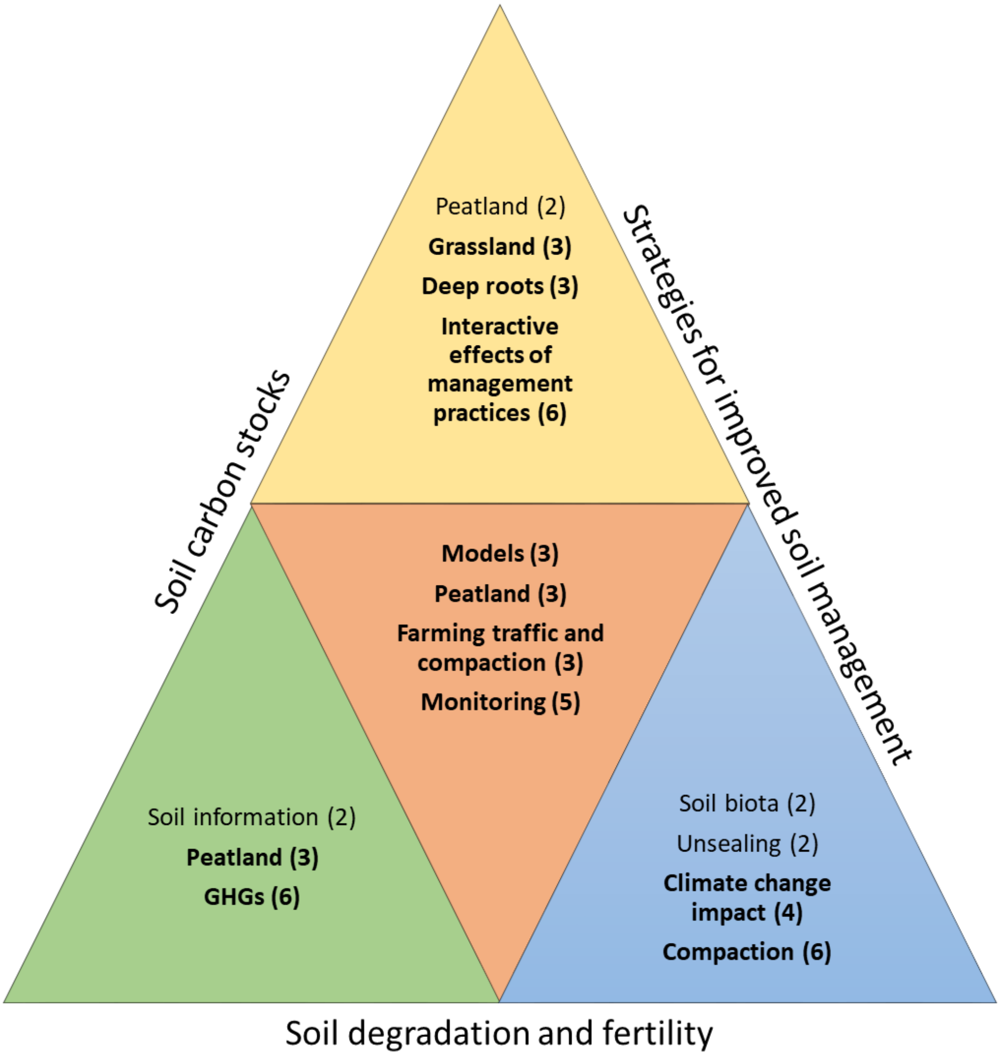

Figure 12. Overlapping subjects of knowledge gaps found in the three different topics (source: syntheses of national inputs; numbers in brackets indicate how many overlapping knowledge gaps were mentioned per issue; issues recurring more than once in this figure are written in bold letters). The sides of the large triangle represent the three topics of this report, the corner triangles show overlapping knowledge gaps between two topics, and the inner triangle shows overlaps between all three topics (orange). Green: overlap between 'Soil carbon stocks' and 'Soil degradation and fertility'; blue: overlap between 'Soil degradation and fertility' and 'Strategies for improved soil management'; yellow: overlap between 'Strategies for improved soil management' and 'Soil carbon stocks'. Details on overlapping knowledge gaps are shown in Table 8 (Appendix B).

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7 Appendix A:

Reporting template for EJP SOIL task 2.2.1

Guidance for completing this template is found in the document: "Guidelines for work package 2 (task 2.1-2.2-2.3)".

Deadline for reporting is 31th of June 2020. For issues regarding completion of the task or the reporting, please contact Lars Munkholm (lars.munkholm@agro.au.dk). Please note that you should just complete one form for each country and that your registration is not completed until you click "Finish".

Please click Next to continue.

Section #1 Background information

Which country do you report from here?

(4) ❑ Austria
(6) ❑ Belgium Flanders
(5) ❑ Belgium Wallonia
(7) ❑ Czechia
(3) ❑ France
(1) ❑ Denmark
(8) ❑ Estonia
(9) ❑ Finland
(10) ❑ Germany
(11) ❑ Hungary
(12) ❑ Ireland
(13) ❑ Italy
(14) ❑ Latvia
(15) ❑ Lithuania
(2) ❑ The Netherlands
(16) ❑ Norway
(17) ❑ Poland
(18) ❑ Portugal
(19) ❑ Slovakia
(21) ❑ Slovenia
(20) ❑ Spain
(22) ❑ Sweden
(23) ❑ Switzerland
(24) ❑ Turkey
(25) ❑ United Kingdom

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Which environmental zones are relevant to consider for the country?

(1) ❑ Alpine North
(2) ❑ Alpine South
(3) ❑ Atlantic Central
(4) ❑ Atlantic North
(5) ❑ Boreal
(6) ❑ Continental
(7) ❑ Lusitenean
(8) ❑ Mediterranean Mountains
(9) ❑ Mediterrenean North
(10) ❑ Mediterrenean South
(11) ❑ Nemoral
(12) ❑ Pannonian-Pontic
(13) ❑ Anatolian

What are the main soil challenges in the country?

(1) ❑ Maintain/increase SOC
(2) ❑ Avoid N2O/CH4 emissions
(3) ❑ Avoid peat degradation
(4) ❑ Avoid soil erosion (e.g water/wind/tillage erosion)
(5) ❑ Avoid soil sealing
(6) ❑ Avoid salinization
(7) ❑ Avoid contamination
(8) ❑ Optimal soil structure
(9) ❑ Enhance soil biodiversity
(10) ❑ Enhance soil nutrient retention/use efficiency
(11) ❑ Enhance water storage capacity

Section #2 Descriptive data of the interviews with the scientific community

How many researchers were interviewed in total?

_____

Which environmental zones were covered in your interviews for each of the three topics?

	Carbon stock	**Soil degradation and fertility**	**Strategies for improved soil management**
Alpine North	(1) ❑	(2) ❑	(3) ❑
Alpine South	(1) ❑	(2) ❑	(3) ❑
Atlantic Central	(1) ❑	(2) ❑	(3) ❑
Atlantic North	(1) ❑	(2) ❑	(3) ❑
Boreal	(1) ❑	(2) ❑	(3) ❑
Continental	(1) ❑	(2) ❑	(3) ❑

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	Carbon stock	Soil degradation and fertility	Strategies for improved soil management
Lusitenean	(1) ❑	(2) ❑	(3) ❑
Mediterrenean Mountains	(1) ❑	(2) ❑	(3) ❑
Mediterrenean North	(1) ❑	(2) ❑	(3) ❑
Mediterrenean South	(1) ❑	(2) ❑	(3) ❑
Nemoral	(1) ❑	(2) ❑	(3) ❑
Pannonian-Pontic	(1) ❑	(2) ❑	(3) ❑
Anatolian	(1) ❑	(2) ❑	(3) ❑

How many researchers were interviewed regarding carbon stocks?

University
____
____
____
____
____
____

National institutes
____
____
____
____
____
____

Non-governmental research organizations
____
____
____
____
____
____

How many researchers were interviewed regarding soil degradation and fertility?

University
____
____
____
____
____
____

National institutes
____
____
____
____

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	____
	____
	____
	____
Non-governmental research organizations	____
	____
	____
	____

How many researchers were interviewed regarding strategies for improved soil management?

	____
	____
University	____
	____
	____
	____
	____
	____
National institutes	____
	____
	____
	____
	____
	____
Non-governmental research organizations	____
	____
	____
	____

What are the main soil challenges covered in your interviews with the scientific community and desktop review?

(1) ❑ Maintain/increase SOC
(2) ❑ Avoid N2O/CH4 emissions
(3) ❑ Avoid peat degradation
(4) ❑ Avoid soil erosion (e.g water/wind/tillage erosion)
(5) ❑ Avoid soil sealing
(6) ❑ Avoid salinization
(7) ❑ Avoid contamination
(8) ❑ Optimal soil structure
(9) ❑ Enhance soil biodiversity
(10) ❑ Enhance soil nutrient retention/use efficiency
(11) ❑ Enhance water storage capacity

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What were the main farm management categories covered in your interviews and desktop review?

(1) ❑ Agricultural systems
(2) ❑ Buffer strips and small landscape elements
(3) ❑ Crops/crop rotations
(4) ❑ Organic matter and nutrient management
(5) ❑ Tillage and traffic
(6) ❑ Crop protection
(7) ❑ Water management

How many documents did you retrieve based on the interviews and desktop review for each of the 3 topics?

Carbon stock	______________________________
Soil degradation and fertility	______________________________
Strategies for improved soil management	______________________________

Which document types did you retrieve based on interviews and desktop review for carbon stocks?

Reviewed journal papers	______________________________
Report	______________________________
Etc.? (Hvilke kategorier vil i mere have?)	______________________________

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____
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____

Which document types did you retrieve based on interviews and desktop review for soil degradation and fertility?

Reviewed journal papers	____
Report	____
Etc.? (Hvilke kategorier vil i mere have?)	____

Which document types did you retrieve based on interviews and desktop review for strategies for improved soil management?

Reviewed journal papers	____
Report	____
Etc.? (Hvilke kategorier vil i mere have?)	____

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____
____

Section #3 National report on knowledge availability

Below please insert a 1-page (excluding references) input to each of the three chapters (1. Carbon stock, 2. Soil degradation and fertility, 3. strategies for improved soil management). This input should include information on:

1) Country and environmental zones addressed

2) Description of the state of knowledge in your country on the specific topics (Carbon stock, Soil degradation and fertility or Strategies for improved soil management) with reference to key publications. Important soil challenges in your country and soil management strategies to address these challenges needs to be described. Important to take account of environmental zones.

3) Identified knowledge gaps seen from a national point of view for the three specific topics (1. Carbon stock, 2. Soil degradation and fertility, 3. Strategies for improved soil management). Important to describe knowledge gaps as seen from both a farm management and a soil policy point of view. This should also include knowledge gaps in terms of modelling and monitoring.

Please insert a 1-page input regarding carbon stocks

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Please insert a 1-page input regarding soil degradation and fertility

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Please insert a 1-page input regarding strategies for improved soil management

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Section #4: Ending

Other reflections regarding knowledge on and use of knowledge on sustainable soil management?

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Please provide the name and e-mail of the person responsible for completing task 2.2.1

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The reporting template is submitted when you click "finish" below, you will not receive a copy of the reporting.

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8 Appendix B:

Table 8: *List of overarching knowledge gaps grouped according to topics indicated in Fig. 10 (colours in the table are connected to the figure; green: overlaps of knowledge gaps between „soil carbon stocks" and „soil degradation and fertility", yellow: overlaps between „soil carbon stocks" and „strategies for improved soil management", blue: overlaps between „soil degradation and fertility" and „strategies for improved soil management", orange: overlaps between the three topics).*

Carbon and Degradation	Degradation and Management	Carbon and Management	Overlaps between the three topics
Peat: • Accurate estimation of degraded peat land • Updated maps of peatland • Quantification of current peatland coverage	**Compaction:** • Comprehensive research on agricultural machinery effects on soil structure and plant growth • Investigation on the usefulness of advanced techniques for detecting field soil compaction • The link between compaction risk assessment and machine control software • Regulations to prevent soil structure degradation • Assessment of management practices to mitigate subsoil compaction • Science-based policy on soil erosion control and soil structure degradation –incentives	**Peat:** • Evaluation of different practices for peatland restoration • Research on how rewetted peat soils can be cultivated without increasing GHG emissions	**Models:** • Models for scenario analysis • Modelling SOC at different scales and for climatic conditions • Evaluation of different management practices under a climate change scenario
GHG: • GHG emissions under different agricultural management practices • Monitoring of GHG emissions in long term experiments • Comprehensive research on GHG emissions from agricultural soils and peatlands • Quantification of GHG emissions from peatlands • Monitoring programmes on GHG emissions • National monitoring of GHG emission of peat soils	**Climate change impact:** • Studies on the impact of climate change on salinization risk • Impact of changing climate on soil biodiversity • Studies on the impact of climate change on soil functions and measures to mitigate the impact • Evaluation of the impact of changing climate on peatland degradation	**Grassland:** • Research needs regarding C sequestration effected by management in grassland soils • Assessment of SOC storage in grasslands/rangelands • Evaluation of the impact of different grassland management systems on the SOM content and the C cycle	**Peat:** • Quantification of peatland degradation • A quantification of C loss rates in peat soil • Quantification of drainage and tillage effects on peatlands
Soil information: • Available soil information at a	**Soil biota:**	**Deep roots:**	**Monitoring:** • Lack of monitoring/insufficient

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sufficient temporal and spatial resolution → major limitations to related estimations and modelling • Inclusion of spatial variability in long term soil fertility measurements	• Knowledge of soil biota contribution to the recovery of degraded soil • Studies focussed on soil microbiota activity/composition and contribution to soil health	• Carbon input in the subsoil by roots of different crops and ways to modify them • Potentials of deep roots and subsequent subsoil C sequestration and vulnerability • Assessments of deep-rooted crops as potential bio-subsoilers	monitoring of mineral soils • Monitoring of SOC changes in long term experiments • Insufficient monitoring of mineral soils • Monitoring SOC at different scales and for climatic conditions • Monitoring programme on SOC
	Unsealing: • Evaluation of the impact of unsealing on soil functions • Investigate unsealing and soil's potential after restoration	**Interactive effects of management practices:** • Biochar, its risks and potentials • Effects of roots and biochar on SOC stocks • Evaluation of cover crops mixtures, bio-residue and biochar effects on soil structure • Effects of management practices such as residues retention, biochar application and cover/catch crop establishment on SOC • Evaluation of short- and long-term effects of combined soil management practices on SOC stock and productivity • Long-term field experiments to evaluate the potential of amendments (including biochar) on soil C stock	**Farming traffic and compaction:** • Farming traffic should be reduced, as it can cause disturbances and compaction • Studies on traffic effect on subsoil compaction • Studies on the use of controlled traffic farming and its effects on soil structure

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