# Sustainable soil management: Soil knowledge use and gaps in Europe

Martin Hvarregaard Thorsøe, Saskia Keesstra, Maarten de Boever, Kristina Buchová, Frederik Bøe, Nádia L Castanheira, Claire Chenu, Sophie S. Cornu, Axel Don, Julia Fohrafellner, et al.

# Sustainable soil management: Soil knowledge use and gaps in Europe

Published in: *European Journal of Soil Science 74.6 (2023): e13439*

## Authors

1. Martin Hvarregaard Thorsøe, Orcid: 0000-0001-7283-7174 (Department of Agroecology, Aarhus University)
2. Saskia Keesstra, Orcid: 0000-0003-4129-9080 (Wageningen University & Research)
3. Maarten De Boever, Orcid: 0000-0001-9352-0475 (Flanders Research Institute for Agriculture, Fisheries and Food)
4. Kristina Buchová, Orcid: 0009-0008-6365-4972 (National Agriculture and Food Centre- Soil Science and Conservation Research Institute)
5. Frederik Bøe frederik.boe@nibio.no Orcid: 0000-0002-3802-2681 Division of Environment and Natural Resources, Department of Soil and Land Use, Norwegian Institute of Bioeconomy Research, Oluf Thesens vei 43, 1433 Ås, Norway. Soil Physics and Land Management, Wageningen University & Research, Droevendaalsesteeg 4, 6708 PB Wageningen, the Netherlands
6. Nádia L. Castanheira Orcid: 0000-0002-9276-1805 (Instituto Nacional de Investigação Agrária e Veterinária, I.P., Soil Lab, Avenida da República, Quinta do Marquês, 2780-157 Oeiras, Portugal)
7. Claire Chenu(ORCID: 0000-0001-9054-0489 Université Paris-Saclay, INRAE, AgroParisTech), 91123 Palaiseau, France)
8. Sophie Cornu (ORCID: orcid.org/0000-0002-2433-5898; Aix-Marseille Univ, CNRS, IRD, INRAE, Coll France, CEREGE, 13545 Aix en Provence Cedex 4, France)
9. Axel Don (ORCID: https://orcid.org/0000-0001-7046-3332; Thünen Institute of Climate-Smart Agriculture, Germany)
10. Julia Fohrafellner Orcid: 0000-0001-5734-7353 (BIOS Science Austria, Silbergasse 30/3, 1190 Vienna, Austria)
11. Roberta Farina Orcid: 0000-0003-4378-0484 (Consiglio per la ricerca in agricoltura e l'analisi dell'economia agraria, Rome)
12. Dario Fornara Orcid: 0000-0002-5381-0803 (Davines Group-Rodale Institute European Regenerative Organic Center (EROC)
13. Maria da Conceição Gonçalves Orcid: 0000-0002-5980-0294 (Instituto Nacional de Investigação Agrária e Veterinária, I.P., Soil Lab, Avenida da República, Quinta do Marquês, 2780-157 Oeiras, Portugal)
14. Morten Graversgaard, Orcid: 0000-0001-7636-4335 (Department of Agroecology, Aarhus University)
15. Olivier Heller (Agroscope, Agroecology and Environment Department, Soil quality and use group, olivier.heller@agroscope.admin.ch, https://orcid.org/0000-0002-5918-4161, Reckenholzstrasse 191, 8046 Zürich, Switzerland)
16. Erich Inselsbacher, Orcid: 0000-0001-5490-8768 (University of Natural Resources and Life Sciences, Vienna, Austria)

17. Anna Jacobs, (ORCID: https://orcid.org/0009-0006-6744-0694; Coordination Unit Climate and Soil at Thünen Institute, Germany; present address: Institute of Sugar Beet Research, Holtenser Landstrasse 77, 37079 Göttingen, Germany, jacobs@ifz-goettingen.de
18. Sara Mavsar Orcid: 0009-0004-0779-8796 (Biotechnical Faculty, University of Ljubljana)
19. Katharina H. E. Meurer, Orcid: 0000-0002-8880-9650 (Department of Soil & Environment, Swedish University of Agricultural Sciences - SLU, Uppsala)
20. Rok Mihelič Orcid: 0000-0002-6845-1903 (Biotechnical Faculty, University of Ljubljana,)
21. Lilian O'Sullivan Orcid: 0000-0002-5333-5758(Teagasc, Crops, Environment and Land Use Programme, Johnstown Castle, Wexford, Ireland)
22. Mansonia Pulido-Moncada Orcid: 0000-0002-8920-8160 (Department of Agroecology, Aarhus University, and DAFNAE, University of Padua
23. Greet Ruysschaert (ORCID: https://orcid.org/0000-0001-6735-0337; Flanders Research Institute for Agriculture, Fisheries and Food (ILVO), Merelbeke, Belgium)
24. Michal Sviček Orcid: 0009-0006-1476-4118 (National Agriculture and Food Centre- Soil Science and Conservation Research Institute; Trenčianska 55; 821 09; Bratislava;+421 2 48206976
25. Mika Tähtikarhu Orcid: 0000-0002-1277-2951 (Natural Resources Institute Finland)
26. Silvia Vanino Orcid:0000-0001-5837-509X (Consiglio per la Ricerca in Agricoltura e l'Analisi dell'Economia Agraria)
27. Wieke Vervuurt Orcid: 0000-0002-0474-0597 (Wageningen University & Research)
28. Sophie Zechmeister-Boltenstern Orcid: 0000-0001-5839-5904 (University of Natural Resources and Life Sciences, Vienna, Austria)
29. Lars Juhl Munkholm Orcid: 0000-0002-4506-9488 (Department of Agroecology, Aarhus University)

**Abstract:**

Soils are the foundation of agricultural production, ecosystem functioning and human well-being. Bridging soil knowledge gaps and improving the knowledge system is crucial to meet the growing EU soil policy ambitions in the face of climate change and the ongoing trend in soil degradation. The objective of this article is to assess the current state of knowledge, knowledge use and knowledge gaps concerning sustainable soil management in Europe. This study is based on interviews with 791 stakeholders and 254 researchers and on a comprehensive review of >1,800 documents carried out under the European Joint Programme (EJP) on agricultural soils. Despite differences in stakeholder groups, the conclusions are rather consistent and complementary. We identified major knowledge gaps with respect to 1) soil carbon stocks, 2) soil degradation and fertility, and 3) strategies for improved soil management. Transcending these three areas, particularly the loss of soil organic carbon (SOC), peatland degradation, and soil compaction are most critical, thus, we stress the urgency of developing more models and monitoring programmes on soils. Stakeholders further report that insufficient transfer of existing soil research findings to practitioners is a hindrance to the adoption of sustainable soil management practices. In addition to knowledge production, soil knowledge gaps may be addressed by considering seven recommendations from the stakeholders: 1) raising awareness, 2) strengthening knowledge brokers, 3) improving relevance of research activities and resource allocation for land users, 4) peer-to-peer communication, 5) targeting advice and information, 6) improving knowledge access and 7) providing incentives. We argue that filling and bridging knowledge gaps should be a priority for policy makers and the insights provided in the article may help prioritize research and dissemination needs enabling a transition to more sustainable soil management in Europe.

**Keywords:** Sustainable soil management; Stakeholder involvement; EJP SOIL; Soil use challenges; Soil health; Soil policy

Highlights

1. Assessment of state of knowledge concerning sustainable soil management in Europe
2. Knowledge on stakeholder needs and soil processes is crucial to improve soil management
3. Key knowledge gaps: SOC loss and dynamics, peatland degradation, soil compaction and on improving models and availability of input data
4. Insufficient research transfer to practitioners hinders adoption of sustainable soil management

# 1. Introduction

Soils are the foundation of agriculture and provide crucial ecosystem services, including the production of food and bioenergy crops, feed, fibers, the regulation of groundwater, as well as contributing to resilient agroecosystems associated with soil biodiversity (Bouma & McBratney, 2013). Current intensive farming practices have exposed agricultural soils to a range of negative effects including loss of soil organic carbon (SOC), soil erosion and nutrient leaching, with implications that go beyond the farmland area (FAO, 2015b; IPBES, 2018). The European Commission (EC) assessed that as much as 60-70% of European soils are degraded as a direct result of unsustainable agricultural management practices and soils have lost significant capacity to provide ecosystem services (Veerman et al., 2020). However, soil health status across different geographical areas and in relation to specific soil threats remains uncertain (Ferreira, Seifollahi-Aghmiuni, Destouni, Ghajarnia, & Kalantari, 2022).

There are several policies and legal instruments that refer to soil threats and soil knowledge production. Moreover, soil policy ambitions recently increased at European level, as reflected in the soil strategy, the Nature Restoration Law as well as the proposal for a Soil Health Law (EC, 2021). Although neglected for years, the protection of soils has recently become an important item on the political agenda, particularly in relation to the size of soil carbon pools, which can contribute to mitigating climate change and achieving the ambitions laid out in the European Green Deal (Heuser, 2022; Visser, Keesstra, Maas, De Cleen, & Molenaar, 2019). In response, the European Union (EU) has adopted a Soil Strategy for the EU, which seeks to achieve healthy soils by 2050 based on a framework and concrete measures to protect and restore soils, and to ensure their sustainable use (EC, 2021). In addition, the EC has launched the Mission 'A Soil Deal for Europe', which will support the transition towards healthy soils by 2030 through a series of research and intervention actions (EC, 2022).

In the EU Soil strategy, sustainable soil management is emphasized as the way to prevent degradation and restore unhealthy soils (EC, 2021). Sustainable soil management encompasses a set of practices that are able to maintain the soil in, or restore it to, a healthy condition yielding multiple benefits, including for water and air. These practices increase soil biodiversity, fertility and resilience which are needed for the vitality of rural areas. However, soil management is complex, since a series of soil physical, biological and chemical processes must be accounted for, and soils and soil properties are diverse across different scales. Furthermore, soil management is connected with a range of aspects like different land-uses, pedo-climatic conditions, access to inputs, machinery, technology, multiple public policies and socio-cultural values (Hessel et al., 2022; Ingram & Mills, 2019; Thorsøe et al., 2019). According to the World Soil Charter, soil management is sustainable if the supporting, provisioning, regulating, and cultural services provided by the soil are maintained or enhanced without significantly impairing either the soil functions that enable those services or biodiversity (FAO, 2015a). However, soil management decisions often involve trade-offs between mutually excluding outcomes such as mitigation of greenhouse gas (GHG) emissions, yield optimization, biodiversity protection and a range of other important ecosystem services. Moreover, pedo-climatic conditions diverge substantially across Europe and it is important to tailor solutions to these conditions and the specific challenges that prevail (Hessel et al., 2022).

Seeking synergies across soil threats and mitigation measures can simultaneously deliver an impact on several sustainability goals. Therefore, analysing the interconnections, documenting knowledge gaps in research as well as practice and addressing trade-offs, remain critical (Keesstra et al., 2018; Thorsøe et al., 2019). Sustainable soil management should therefore be designed to take soil health as well as socio-economic conditions into account.

To make informed management decisions, efficient policies and ultimately achieve sustainable soil management, there is a need to know the implications of different practices on soil health under different pedo-climatic conditions and to identify key knowledge gaps. This analysis is based on a systemic understanding of knowledge and its role in innovation processes based on an AKIS framework (Agricultural Knowledge and Innovation System). The perspective is widely used to characterize the systemic nature of knowledge and the institutions that support knowledge transfer and use (Klerkx, van Mierlo, & Leeuwis, 2012; Knierim et al., 2015). The AKIS framework emphasizes that successful knowledge production and use require links between actors who are engaged in knowledge production, transfer and use to support decision-making, problem-solving and innovation in agriculture (Klerkx et al., 2012; Knierim et al., 2015).

The systematic and deliberate management of knowledge among key actors is an important aspect of the AKIS in most European countries (Klerkx et al., 2012; Knierim et al., 2015; Labarthe & Beck, 2022). Knowledge management includes important aspects like knowledge production, where knowledge is captured or created, knowledge transfer whereby knowledge is translated and made available to practitioners as well as knowledge use, where practitioners adopt knowledge and change their farming practice (Dalkir, 2005). Within the agri-food sector, various groups of actors are involved in these processes, while knowledge production typically takes place in specialized institutions such as universities or research centres, knowledge transfer is facilitated by knowledge brokers such as the advisory services and finally knowledge is used by farmers or related end users. Within the agri-food sector, public funding facilitates knowledge production, transfer and use in support of policy objectives and to assess and develop effective policies. Ensuring alignment across these three arenas is therefore an important aspect of knowledge management (Dalkir, 2005; Klerkx & Leeuwis, 2009).

In assessing the performance of knowledge management systems, stakeholder participation has gained prominence ensuring that interventions become effective, democratic ideals are fulfilled and to minimise conflicts in land use management (Reed, 2008). Several European research projects consultation have sought to assess the state of soil knowledge using stakeholder consultations.

Although soil data is available at European scale (see for instance Orgiazzi, Ballabio, Panagos, Jones, and Fernández-Ugalde (2018)), there are also substantial gaps in European soil knowledge. With respect to available soil monitoring, van Leeuwen et al. (2017) found that biological and physical attributes were severely under-represented vis a vis chemical parameters. Existing stocktakes of knowledge availability found that research output is generally published in line with the FAIR principles (Findable, Accessible, Interoperable, Reusable) (Potokar, Tomažin, & Škrlep, 2021). However, often these findings are neither directly applicable to practitioners nor are the underlying data or models (Hessel et al., 2022; Labarthe & Beck, 2022; Potokar et al., 2021). Regarding knowledge use in farming, further implementation barriers are complex and involve fragmentation of advisory services as well as lacking end users' capacities (Ingram & Mills, 2019; Ingram et al., 2022). With respect to SOC, Frelih-Larsen (2017) in a stakeholder consultation find that knowledge gaps are particularly about farm-level management practices, their effects, economic costs and benefits. In sum, existing studies of the European AKIS indicate that gaps in knowledge availability and use are complex and regionally diverse, hence to effectively address insufficiencies a thorough analysis is needed.

Against this background, the objective of this article is to assess the state of knowledge, knowledge use and knowledge gaps concerning sustainable soil management in Europe. This assessment is based on inputs from an extensive public consultation among a broad stakeholder group and a group of soil researchers from across Europe. With this approach, we move beyond an assessment of the knowledge gaps from an academic perspective and also discuss opportunities to address these knowledge gaps from a practice and policy perspective. Thus, this supplements already existing assessments of soil challenges (FAO, 2015b; Ferreira et al., 2022; Vanino et al., 2023; Veerman et al., 2020). Further, the synthesis presented here also extends the findings originally presented under the EJP SOIL programme, by providing additional data analysis and aligning with the existing academic literature on soil knowledge use and knowledge gaps.

# 2. Materials and methods

The data that constitute the basis of this article were acquired with two assessments that were completed in the spring of 2020 to develop a roadmap for EU Agricultural Soil Management research within the European Joint Programme on soil (EJP SOIL). EJP SOIL is a research programme on agricultural soil management (2020-2025) co-funded by the EC and the participating European countries (24 in total). EJP SOIL contributes to develop knowledge, tools and an integrated research community to foster climate-smart sustainable agricultural soil management. In each partner country, a broad group of soil stakeholders was formed, the so-called National Hubs, to inquire about their perspectives on various agricultural soil related topics (for more information please see www.ejpsoil.eu). The present article is a synthesis of two sets of23 national reports prepared by each partner, based on a series of interviews with the broad group of stakeholders in the National Hubs and a consultation of key researchers at national level.

Due to the diversity of pedo-climatic conditions across Europe and the specific soil challenges and knowledge gaps, partner countries were grouped into four regions according to the respective environmental zone as classified by Metzger, Bunce, Jongman, Mücher, and Watkins (2005): Central Europe, Northern Europe, Southern Europe (including Turkey) and Western Europe. The four regions were then compiled to identify knowledge gaps hindering the transition towards climate smart sustainable soil management.

In this article, 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).

## 2.1 Perspectives on knowledge availability and use – broad group of stakeholders

The broad group of stakeholders in the assessment consisted of farmers, advisors, representatives of agricultural associations, NGOs, policy makers and the agricultural industry, which were members of EJP SOIL national hubs or were linked to these. Interviews with stakeholders were conducted by the national EJP SOIL members in their local language allowing for the best possible quality of information. Participation in the EJP SOIL National Hubs was voluntary and open, but an initial national identification of key players was conducted, which served as a basis for active recruitment. In total, 791 stakeholders from 23 countries were interviewed for the national reports (Table 1). Interviews were completed primarily as an online survey, but also face-to-face, by phone or video call, or as part of a focus group. Also, the composition of stakeholders varied across countries due to differences in organizational landscape and stakeholder availability. This variation in the number of informants and their related stakeholder categories is a minor shortcoming of the analysis as the perspective and methods of stakeholder consultation varied slightly across countries. Farmers are an important stakeholder category for the objectives of this paper and these were not a part of discussions across all countries since the National Hubs mostly engage stakeholders at an organizational level. However, the practice perspective is also reflected by advisors and representatives from farmers associations and industry. To reduce potential bias, national inputs were consolidated and reported in a structured format with predefined questions by national EJP SOIL partners who were familiar with the local conditions and discussions. Questions were based on experiences from a series of European soil research projects, including RECARE, SoilCare, CIRCASA, LANDMARK, PRO AKIS and AgriLink, addressing five predefined themes: 1) structure of the agricultural soils knowledge system, 2) coordination of knowledge production and use, 3) ability of the knowledge system to influence farming practices, 4) knowledge status relative to environmental zones and 5) knowledge gaps (see Thorsøe (2021) for further methodological details).

Each national partner synthesized interviews and prepared a national report based on a predefined template that included both structured and open questions, enabling comparisons across national contexts. This ensured that we could represent perspectives of individual stakeholders or specific national concerns and reflections. Importantly, when we analyzed national reports, input from each country was presented separately without a regional aggregation to avoid blurring differences in representation as well as other national and regional characteristics and further the length of national reports was comparable. This information was reported in a synthesis of the current knowledge use (Thorsøe, 2021).

## 2.2 Perspectives on knowledge availability and use - researchers

In addition to the interviews with the broad group of stakeholders, a second line of consultations were conducted, addressing a group of researchers. Interviews with researchers identified soil research gaps in national contexts and identifying peer-reviewed research documenting such gaps. Further, inputs from national teams were supplemented with a literature review, here we focussed on <10 yrs. old pan-European and global publications related to sustainable agricultural soil management.

Questions to the scientific community were both structured and open, addressing three themes: 1) carbon stocks, 2) soil degradation and fertility, and 3) strategies for improved soil management. We asked the partners to conduct a series (5-10) of interviews with key researchers for each of the three themes. In total, 254 researchers were interviewed, ranging between 3 and 26 per country and some researchers were interviewed for more than one topic (Table 2). For the different subjects, the number of interviews varied between 148 and 187 and they were subdivided into the following categories: researchers representing universities (42%), national research institutes (46%) and non-governmental institutions (12%). This information was reported in a synthesis on the current knowledge availability (see Munkholm et al. (2021) for further methodological details).

## 2.3 Synthesis

Data from the two rounds of interviews were subsequently included in two reports on the national state of knowledge availability and use. Both reports contain qualitative as well as quantitative elements, thus providing different types of complementary information, offering a rich picture on the knowledge on, and use of knowledge on sustainable soil management (Creswell, 2014).

Replies to the closed questions appear in tables (3-5) and figures (1-2), and represent an assessment of the stakeholders regarding the situation in the partner countries based on the data acquired. Where data is presented in tables and figures, a more detailed description of the process of consolidation is included in the caption. Due to the notable contextual differences and the differing number of replies across countries, replies for each country, environmental zone or region appear separately. Therefore, although the number of respondents varies across countries this quantitative variation does not imply that countries with a higher number of participants carry a higher weight in the analysis as the synthesis of result is conducted as a qualitative analysis.

Open questions were used to deepen insights, highlight and unfold recurring themes thus providing complementary insights. Further, while the assessment of the broad group of stakeholders offers a wide-ranging view of the different challenges in both research and practice, the perspective of the group of researchers is more narrowly focused on particular gaps in the scientific knowledge base. In this way the two assessments offer complementary insights and this joint synthesis offers a comprehensive perspective on soil knowledge gaps in both research, policy making and farming practice.

For the analysis of the qualitative elements, the text which summarized discussions across partner countries was initially coded, and subsequently organized into categories, identifying common themes, shared experiences and patterns. Following, Corbin (1998) and Silverman (2011), initially the text provided by partners was examined line by line, perceptions and concepts of relevance to knowledge use and gaps were identified and coded (labelled). Once a code was assigned, this code was subsequently used to code the remaining text while simultaneously identifying possible new codes. After coding of the entire text, similar codes were grouped into higher order categories that are broader and encompass the content of several codes thus reducing the overall amount of concepts for the analysis. As a result of this process, we identified 7 categories describing the need for improvements to advance sustainable soil management presented in section 3.2.

# 3. Results

## 3.1 Gaps in knowledge about sustainable soil management

In assessing the severity of knowledge gaps, we initially inquired stakeholders about what they perceived to be the most important soil challenges, identifying soil threats where there is a gap between the current state and the desired state. Interviews with the broad group of stakeholders emphasize that maintaining and increasing SOC was not only perceived as very important in most countries; it was also assessed to be a soil challenge with many pressing knowledge gaps (see Table 3). The perceived importance of other challenges was region-specific. Thereby, topics reflected differences in pedoclimatic conditions, land use and farming systems, such as avoiding salinization and contamination in Southern Europe, avoiding erosion in Southern and Central Europe and improving water storage capacity in Central Europe.

While knowledge gaps related to maintaining and increasing SOC were among the most pressing in all regions, other critical knowledge gaps varied more widely across and within regions (see Table 3). In Central Europe, avoiding soil erosion, enhancing soil nutrient retention and nutrient use efficiency and enhancing water storage capacity were considered to be among challenges with the most critical knowledge gaps. Whereas in Northern Europe, avoiding nitrous oxide/methane emissions, ensuring an optimal soil structure and enhancing soil nutrient retention and nutrient use efficiency were assessed to be among the challenges with most critical knowledge gaps. In Southern Europe, knowledge needed to avoiding soil erosion, avoiding contamination and enhancing soil biodiversity were perceived to be among the challenges with most critical knowledge gaps. In Western Europe, the most critical knowledge gaps were associated with the challenges of enhancing soil biodiversity, ensuring optimal soil structure and enhancing water storage capacity.

Interviews with the group of researchers identified specific knowledge gaps focusing on three key areas 1) soil carbon stocks, 2) soil degradation and fertility, and 3) strategies for improved soil management.

***Knowledge gaps with respect to soil carbon stocks***

Knowledge gaps with respect to SOC stocks in Europe are diverse, but many similarities across countries and regions could be identified (see Figure 1). In general, knowledge on the effects of management practices is sparse and there is a lack of monitoring programmes on carbon stocks and data on achievable carbon sequestration potentials. Across all four regions, the group of researchers expressed an urgent need for research on deep carbon in the subsoil (>30 cm depth) and its dynamics and in particular, knowledge on subsoil SOC stocks and their susceptibility to climate change. Additionally, the impact of deep roots on carbon stocks, their contribution to SOC sequestration and ways to effectively include them in modelling SOC dynamics were highlighted as critical knowledge gaps.

Insufficient knowledge about peat soils was highlighted as relevant for all assessed topics in interviews with the group of researchers, i.e. carbon stocks, soil degradation and fertility, and strategies for improved soil management. Since they represent large SOC stocks, peatlands' restoration, re-wetting and management must be improved (see Figure 1). Moreover, they are of particular concern as endangered habitats. An accurate estimation of the area of intact and degraded peatland was assessed to be missing in the Western region. In the Northern region updating maps on groundwater levels and carbon stocks in organic soils was highlighted. Monitoring of peat soils (area, C stocks) was raised as a need in the Central region, as well as monitoring GHG emissions and reliable quantification of C loss rates in the Northern region. Further, there appeared to be a lack of studies on the protection of organic soils by rewetting in the North and in the Central region on how rewetted soils can be used without inducing additional GHG emissions, e.g. with paludiculture. Within the Southern region, no knowledge gaps regarding organic soils were formulated, which is due to the fact that peatlands are hardly present in this region.

***Knowledge gaps with respect to soil degradation and soil fertility***

Across all regions, interviews with the group of researchers indicated the need for long-term experiments in which the effect of agricultural management practices and climate on soil quality and - processes can be assessed. Specifically, in the Northern region requests were made for long-term experiments involving different management practices to assess their impact on soil health. Further, studies on how soils and soil degradation processes in different climatic zones, a soil survey on parameters related to soil degradation and fertility, and the extent of soil degradation processes were stated as pressing knowledge gaps. In the Central region, the need for long-term experimental field trials to assess the influence of different soil management practices on soil processes was expressed, similarly to the Northern region. The Western region highlighted the need for further evaluations of the impact of climate change on soil degradation and soil fertility, the need for comprehensive studies on soil degradation and fertility challenges and their interactions, the development/introduction of simple soil health indicators that could be applied by farmers, and the need for a science-based policy to prevent soil degradation. Lastly, the Southern region expressed 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.

The group of interviewed researchers also drew attention to subsoil compaction as a severe and long-lasting outcome of heavy field traffic (particularly on wet soils). Although comprehensive knowledge on drivers of soil compaction and its effects was available across all regions, a need for assessing the extent on a national level and impacts of subsoil compaction on plant production and system resilience towards climate change was expressed. Further, more insights into the persistence of compaction and the potential impact of climate change was assessed as a shortcoming.

***Knowledge gaps with respect to strategies for improved soil management***

The results of interviews with researchers indicated that knowledge gaps in three key areas of research on strategies for improved soil management are important. Firstly, organic matter and nutrient management, particularly an improved mechanistic understanding of the impact of organic amendments, carbon storage in soils and cycling under grassland management. Secondly, regarding crops, crop rotations and perennial cropping, knowledge gaps include studies on the potentials for increased perennialization, and on optimization of perennial cropping to provide multiple ecosystem services (e.g., limit trade-offs between carbon sequestration and N2O emissions). Further, gaps with respect to cover crops, cover crop mixtures, deep-rooted crops and intercropping as means to achieve multiple benefits (soil biodiversity, improved fertility and soil health, carbon storage, etc.) were emphasized. Thirdly, with respect to tillage and traffic, a need for an improved mechanistic understanding of tillage effects on carbon storage in soils, N2O emissions and the interaction of several factors including soil type, carbon and nitrogen status and temperature was mentioned. Fourthly, effects of different combinations of management practices were emphasized. A challenge for research is that the information provided by farmers is often not sufficiently detailed to isolate the specific effects of different combinations of management practices used for crop cultivation. Lastly, a need for comprehensive studies on the effects of reduced tillage and no-tillage on soil processes/properties and ecosystem services as well as an assessment of management practices to mitigate subsoil compaction was expressed.

***Functional linkages across soil knowledge gaps***

Due to functional linkages and because issues of special concern recur across topics and countries, we stress three research areas of special concern based on input from researchers and review of literature (see Figure 2). These include (i) peatlands (an endangered habitat type representing large carbon stocks, in need for new management strategies), (ii) soil compaction (requiring new management strategies, affecting carbon stocks and causing degradation) as well as (iii) more models and monitoring (tools which are relevant in relation to all soil challenges).

## 3.2 Addressing knowledge gaps about sustainable soil management

Aside from addressing the knowledge gaps identified above, interviews with the broad group of stakeholders indicated the need for a number of improvements to advance sustainable soil management. A range of actions to improve soil knowledge were perceived by stakeholders as either important or very important across partner countries, though particularly pronounced in the Northern region (see Table 5). Generally, a number of undertakings were considered very important across partner countries, including improving soil monitoring, developing new management strategies, increasing the availability of existing research for stakeholders, and improving coordination of knowledge production between stakeholders (Table 5).

***Gaps in knowledge transfer***

Interviews with the broad group of stakeholders indicated a range of divergences across countries with respect to the overall effectiveness of the current AKIS in communicating about sustainable soil management to practitioners (see table 4). In a number of countries, the current system for knowledge dissemination is considered ineffective, including Italy, the United Kingdom, Austria, Portugal, Switzerland, the Netherlands, Lithuania and Latvia. However, in other countries, the perception is more positive, particularly in Denmark and Belgium (Wallonia). Although there are some commonalities across Europe, stakeholders indicate that in the dissemination of sustainable soil management practices, the national context and the particular challenges faced by the local AKIS are important to consider.

Further, interviews indicated that insufficient knowledge production and transfer due to reliance on project funding often cause research discontinuity. This is a challenge as soil research requires long-term documentation since management effects can often only be detected in long-term field experiments or soil monitoring programmes. Moreover, research from universities was criticised to often lack applicability for farmers and for an insufficient coordination between policymakers, researchers and farmers. Challenges, for instance, arise because the theoretical knowledge produced at universities was considered irrelevant or difficult to access for farmers. Furthermore, current research was criticised to insufficiently support the integrated decision-making of farmers and policymakers, where different challenges, trade-offs and synergies need to be balanced.

The broad group of stakeholders was given the opportunity to provide further reflections on how to address the knowledge gaps. Inputs from interviews were summarised in seven main topics:

***1) Raising awareness***

On a general level improving practitioners' understanding of soil-related processes as well as their capacity and ability to adopt sustainable soil management practices were emphasized as important elements, since a general raise in awareness is a precondition for engaging with sustainable soil management.Practitioners are generally concerned about their soil, but may lack the ability to properly implement sustainable soil management. A general awareness raising among consumers for 'soil-friendly' products was emphasized as an enabling factor for promoting interventions in the value chain, as a price premium for 'soil-friendly' could be used to fund sustainable soil management. Across Europe, several incentive programmes and small scale initiatives indicate that it is possible to use the value-chain to promote sustainable soil management and raise awareness. Initiatives i.e. include Terre de Liens in France, Kulturland in Germany and a range of community supported farms in the Nordic region. Raising awareness is also needed for policymakers to allocate resources for soil research and soil policy development. Further, it was indicated that practitioners are difficult to reach in a communicational context due to time and resource constraints, setting aside sufficient resources for the mobilisation of participants to communicational activities is therefore an important precondition. Further, choosing appropriate communication channels that all stakeholders use, such as farmers magazines, conventions and participation in field days appeared to be important. The following points further detail some of the elements that assist in bridging gaps in knowledge transfer.***2) Strengthening knowledge brokers***

Budget for knowledge dissemination in national and European research projects was reported being often too limited to have a significant impact. Although financial support for dissemination is sometimes sufficient, resources were not always found to be allocated appropriately, i.e. for activities that actually build capacities with practitioners or that address relevant knowledge gaps. This was particularly perceived to be important in Germany, the Netherlands and the Baltic states. Using knowledge brokers to leverage sustainable soil management was indicated to be important to improve dissemination, including training programmes for farmers and advisors, that have a direct relationship with farmers is emphasized to be important.

***3) Improving the relevance of research activities and resource allocation for land users***

Some stakeholders suggested that involving knowledge users in different stages of the research process can increase the practical relevance of the research outcomes. Thus, transdisciplinary research in which researchers directly collaborate with end users to co-create knowledge should be initiated. Thus, thoroughly assessing knowledge needs before initiating communication campaigns and engaging farmers i.e. in surveys or focus groups can improve relevance. Although it is often not relevant to include farmers directly in performing research activities as such, it was emphasized that farmers may contribute to developing research ideas and testing solutions in practice. Interviews also indicated that this may be achieved by allocating additional resources for projects that include farmers or engaging farmers in discussion forums..

***4) Peer-to-peer communication***

Peer-to-peer networks and communication were emphasized as very useful platforms to exchange knowledge about sustainable soil management, particularly between the research community and the within the farming sector. Interviews indicate that practitioners generally prefer to learn from peers and that the bottom-up approach of such networks provide a platform for communication about sustainable soil management that does not emanate from research institutions. However, according to stakeholders, there are only a few peer groups that focus on soil-related issues, but these are perceived to be good options for such activities. In addition, it is emphasized that peer-to-peer communication also offers opportunities for innovative first-movers to share their experiences. Dissemination involving farmer associations was proposed as another effective communication channel which may help to address traditional and highly ingrained practices. Further, demonstrations using real-life examples were found to be effective because farmers can see and learn from results in practice. Demonstration fields, pilot farms or seminars for soil conserving and improving practices were indicated to be an essential component as well. This was also suggested as a way to transfer solutions from one country to the other.

***5) Targeting advice and information***

Particularly for practitioners in localities with heterogeneous geography, it was indicated to be of importance that advice and recommendations are specific to spatial contexts to ensure relevance and usability. Interviews indicated a number of elements that could be strengthened to improve site-specificity, including smartphone apps and other online decision support tools. Furthermore, soil analysis was pointed out as an important element in targeting advice, but in some regions lacking data could be an obstacle.

***6) Improving knowledge access***

Knowledge on sustainable soil management was often found to be fragmented across different researcher groups, institutions, or even across countries, thus creating the need to compile knowledge and make it more approachable. Although likely diverging across countries, interviews with the broad group of stakeholders emphasized that digital communication, which has a broad reach, is important to improve the availability of knowledge, including datasets, research results and successful management strategies. It was suggested that accessible and comprehensive web-based platforms for gathering and disseminating comprehensive national datasets if these already exist (as well improving the resolution of the European datasets base) for instance integrating with social media to facilitate online networking and community building. Soil maps were found to be difficult to understand for outsiders, therefore, highlighting implications for practitioners were indicated as an aspect in need of improvement. It is emphasized that this could be ensured, e.g. by developing decision support tools that provide comprehensive advice on farmers' field practice, on nutrient application, manure management, pest management, field traffic or other important issues. Locally some decision support tools have been developed, such as Terranimo® (https://www.terranimo.dk/) for assessing the effects of field traffic, but translation and a joint decision support platform is requested.

***7) Providing incentives***

Although practitioners are interested in sustainable soil management, stakeholders informed that they often cannot implement recommendations due to economic constraints. Interviews in the broad group of stakeholders indicated that sustainable soil management practices which merely provide public benefits, were not always a key priority for land users vis a vis improving productivity or yield stability. Further, since much dissemination was carried out by farmers' associations and by advisors, it was emphasized that a shift in the perception of sustainable soil management within these stakeholder groups is needed, which could partly be achieved by strengthening economic incentives to highlight the societal importance. Incentives would ensure that practitioners have the means to implement sustainable soil management if they have the capacity. Therefore, financial incentives are important to motivate practitioners to engage in learning programmes and implementing changes in soil management. Initiatives can include subsidies or taxes. Highlighting economic benefits of sustainable soil management, e. g. by labels, may also be useful to stakeholders.

# 4. Discussion

## 4.1 Soil knowledge use and gaps

Across Europe, we found considerable variation in soil knowledge use and gaps with varying importance for sustainable soil management. These findings reflect the diverse pedoclimatic conditions and farming systems across Europe, as also emphasized in other studies (Frelih-Larsen, 2017; Hessel et al., 2022; Strauss, Paul, Dönmez, Löbmann, & Helming, 2023; Vanino et al., 2023). Lacking knowledge use may either be the result of unavailability or insufficient transfer. Our study finds both deficiencies, but the situation across the surveyed countries varied considerably.

In this assessment we focused on a broad stakeholder group, and a more narrow group of soil researchers. The group of researchers focused on identifying pertinent research topics, including the need for improving soil monitoring, long-term experiments and management strategies, particularly with respect to SOC and nutrients. The broad group of stakeholders adopted a wider perspective emphasizing the need to adjust research in order to meet the knowledge needs of farmers, to coordinate and to disseminate research findings to ensure the foundations for sustainable soil management.

Hence, these two groups provided complementary insights on current soil knowledge use and gaps, as well as on opportunities for addressing these gaps. Thereby, the broad group of stakeholders focused on the wider aspects of the European AKIS, while researchers focused more narrowly on pertinent research topics.

Although diverging in composition and perspectives, the two groups both identified a number of gaps in current knowledge availability and use, particularly with respect to SOC. Thus, we argue that the main knowledge gaps are related to relevant soil threats (particularly loss of SOC, peatland degradation, soil compaction), developing more models and monitoring programmes, and effectively disseminating knowledge. This reflects that mitigating climate change and preventing soil degradation using sustainable soil management practices has become an important concern across Europe in policy as well as among practitioners. Further, across regions, the group of researchers expressed an urgent need for research on deep carbon in the subsoil and its dynamics and susceptibility to climate change.

However, given the composition of EJP SOIL, a number of countries in South and Southeast Europe are not included in this assessment, including, Spain (not represented in the broad group of stakeholders), Romania, Greece and the Balkans. Thus, in the ongoing Soil Mission research it is important to ensure that the soil challenges that are prevalent in these countries are also considered. A series of recent assessments of the soil health status and soil challenges in the region indicate that challenges for these countries are comparable to other Mediterranean countries. E.g. erosion and desertification are challenges across all countries (Petrescu-Mag, Petrescu, & Azadi, 2020; Ristić et al., 2020; Schismenos, Emmanouloudis, Stevens, Katopodes, & Melesse, 2022), whilst contamination and soil sealing are also highlighted as additional issues across the Balkans (Ristić et al., 2020). Further, as previously noted, although farmers are an important stakeholder category they were not part of discussions across all countries. Therefore, additional knowledge gaps may have featured more prominently if the composition of the stakeholders were different, including gaps relating to the productive potential of farmland, such as irrigation, liming and, nutrient management.

## 4.2 General implications for bridging knowledge gaps

To improve the AKIS and effectively address key soil challenges, such as the loss of SOC, poor nutrient management, soil erosion, soil compaction and soil biodiversity loss, the coordination of a broad suite of actors, including researchers, policy makers, practitioners and knowledge brokers is required (DeCaro, Chaffin, Schlager, Garmestani, & Ruhl, 2017; Folke, Hahn, Olsson, & Norberg, 2005; Klerkx, 2020; Knierim et al., 2015). Further, measures with multiple beneficial effects on soils often imply systemic changes in the farming system, as sustainable soil management is interlinked with a number of farming operations (Strauss et al., 2023). However, as documented in this article, the fragmented knowledge infrastructure and the lack of collaboration among different user groups and scientific disciplines is of concern. If not overcome, this will hamper the ability of EU Member States to meet the ambitious objectives of achieving land degradation neutrality, land-based climate neutrality by 2035 and good soil health by 2050 as agreed in the EU soil strategy (ECA, 2021). Ongoing degradation of soils, which contain large carbon stocks, including of agroforestry systems and peatland ecosystems, where trees are cut or peatland drained (McDonald et al., 2021; Tanneberger et al., 2021) indicates that soil use knowledge gaps are critical to fill as a basis for meeting the wider strategic objectives of the European Commission.

In line with others, we contend that it is unlikely that increasing knowledge production and knowledge transfer alone will not be sufficient to ensure a transition to sustainable soil management (Dalkir, 2005; Ingram & Mills, 2019; Ingram et al., 2022; Rust et al., 2020; Thorsøe et al., 2019). It also needs to be recognized that knowledge is embedded in a wider socio-material context that enables or constrains the implementation of sustainable soil management, e.g. size and type of farm machinery or mode of regulation (Huber-Stearns et al., 2017; Thorsøe et al., 2022; Visser et al., 2019). Further, various socio-cultural aspects like trust, norms, connectedness and power influence the capacity, ability and motivation of farmers to change their soil management practices (Rust et al., 2020). This implies that a wide range of enabling conditions must be provided to ensure a transition to sustainable soil management. Therefore, ensuring that supporting policies, technological development, sociocultural perceptions, economic and market incentives, are all aligned with the creation of research infrastructures and with new knowledge production and application is important (Brady et al., 2022; Markard, Geels, & Raven, 2020).

Assessments of knowledge transfer via advisory programmes under the CAP programmes have revealed that few farmers are reached and advise is insufficiently targeted to groups with specific knowledge needs (Labarthe & Beck, 2022). Particularly with respect to sustainable soil management, multi-scale character and diverse audience for advise constitute a complex arena for changing farming practices (Ingram & Mills, 2019). Further, other European wide surveys indicate that farmers diversity and the plurality of European farm advisory services constitute a hindrance to adoption of sustainable management practices) (Madureira, Labarthe, Marques, & Santos, 2022). On top of that, the profound differences in pedo-climatic conditions and institutional approaches to soil management interventions across European countries call for a greater simplification and coherence of policy actions to ensure that national initiatives are adapted to local conditions (Hessel et al., 2022; Ingram & Mills, 2019).

### 4.3 Bridging knowledge gaps in the EU Mission A Soil Deal for Europe

The gaps in soil knowledge availability and use identified in our study may help to focus and prioritize place-based research on sustainable soil management. However, the nature of current soil challenges and their complexity imply that a simple linear research, policy and implementation logic is inadequate, but rather a systemic approach is needed in order to effectively address relevant issues (Bouma, de Haan, & Dekkers, 2022).

At EU level, the Mission 'A Soil Deal for Europe' is rather ambitious in terms of allocating funds for research on soil biophysical processes, economic incentives and sociocultural drivers as well as for communication and demonstration activities for instance by the establishment of 100 Living Labs as well as the EU-FarmBook platform (EC, 2022). Living Labs are broadly defined as: "*User-centred, place-based and transdisciplinary research and innovation ecosystems, which involve land managers, scientists and other relevant partners in systemic research and co-design, testing, monitoring and evaluation of solutions, in real-life settings, to improve their effectiveness for soil health and accelerate adoption*" (EC, 2022). Given the complexity and the uncertainties related to agro-ecosystems, Living Labs can be an essential component in improving the coordination of knowledge production (McPhee et al., 2021). Further, Living Labs as a platform that brings together researchers, practitioners, policy makers, and the general public may be an important component in identifying and addressing wicked soil challenges (Bouma et al., 2022). Showcasing sustainable solutions in practice-based settings and designing national policies that present these solutions in specific contexts can strengthen farmers' capacities and abilities to adopt sustainable soil management practices (Beaudoin et al., 2022).

Although the Soil Mission and the proposal for a Soil Health Law presents a window of opportunity for a transition towards sustainable soil management, there is currently no comprehensive coordination to address soil threats and soil-related issues in the EU (Heuser, 2022). Further, other issues beyond climate change also need consideration to ensure the fulfilment of the wider sustainability goals of society, including biodiversity, food security and various socio-economic issues (FAO, 2015a; IPBES, 2018). Working towards greater coherency of the EU policy architecture will help to improve sectoral coordination and the full domestic implementation of current EU policies. Therefore, actions to protect soils should not constrain our abilities to address these other key societal challenges, but rather we should strive for synergies by working towards integrated systemic solutions (Alrøe & Noe, 2014).

However, a range of identified shortcomings in the implementation of existing policy architecture, such as trade-offs across policy siloes. These e.g. include, increasing carbon sequestration versus minimizing nutrient inputs) as wells as shortcomings in the allocation of CAP funding, supporting drainage versus protecting carbon stocks, these shortcomings critically prevent a transition to sustainable soil management and must also be addressed (Keesstra et al., (in review)). Therefore, aside from addressing knowledge gaps, policies must also provide an enabling environment for development of novel solutions and incentives for the adoption of sustainable soil management practices by farmers.

# 5. Conclusion

The objective of this study was to assess the state of knowledge, knowledge use and knowledge gaps concerning sustainable management of agricultural soils in Europe. This is particularly important to meet the soil policy ambitions in face of climate change and ongoing soil degradation.

Based on two complementary assessments, provided by a broad group of stakeholders and by the group of researchers, we identified a series of knowledge gaps with respect to sustainable soil management in Europe. Despite differences in perspectives, the conclusions from the two groups are rather consistent and complementary. Important knowledge gaps regarding relevant soil threats (particularly loss of SOC, peatland degradation, and soil compaction), developing more models and monitoring programmes, but also communication between stakeholders, especially researchers and practitioners, were found. Stakeholders further provided their reflections on how to address these knowledge gaps, which have been summarised in seven recommendations: 1) raising awareness, 2) strengthening knowledge brokers, 3) improving relevance of research activities and resource allocation for farmers, 4) peer-to-peer communication, 5) targeting advice and information, 6) improving knowledge access and 7) providing incentives. Filling these knowledge gaps and involving stakeholders in the process should be an important policy concern and this study may help prioritize research and dissemination needs according to the raised knowledge gaps. This is needed to provide solutions that prevent policy incoherencies, ensure synergies with other societal concerns and an enabling environment that ensures the adoption of sustainable soil management across Europe.

# Tables and figures

**Table 1:** Composition of the broad group of stakeholders (Thorsøe, 2021).

| | | Policy-makers | Research communities | Research funders | Educational institutions and | Farmers & demonstration farms | Advisors | Farmers' organisation | Agro-industry, supply & retail | Laboratories | National science testing and verification centers etc. | NGOs | Others | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Central Europe** | Austria | 1 | 4 | 0 | 3 | 0 | 2 | 1 | 0 | 0 | 0 | 0 | 0 | 11 |
| | Czechia | 1 | 3 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 0 | 11 |
| | Germany | 2 | 80 | 0 | 6 | 204 | 28 | 0 | 6 | 0 | 0 | 9 | 75 | 410 |
| | Hungary | 2 | 3 | 0 | 2 | 1 | 2 | 2 | 2 | 2 | 1 | 1 | 0 | 18 |
| | Poland | 2 | 1 | 0 | 0 | 5 | 2 | 0 | 1 | 1 | 0 | 0 | 0 | 12 |
| | Slovakia | 2 | 3 | 0 | 2 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 9 |
| | Slovenia | 1 | 13 | 0 | 2 | 0 | 9 | 1 | 0 | 0 | 0 | 0 | 0 | 26 |
| | Switzerland | 9 | 7 | 0 | 4 | 0 | 3 | 3 | 4 | 0 | 1 | 0 | 0 | 31 |
| | **Total** | **20** | **114** | **1** | **20** | **211** | **46** | **9** | **13** | **5** | **3** | **11** | **75** | **528** |
| **Northern Europe** | Denmark | 4 | 10 | 0 | 0 | 4 | 2 | 6 | 1 | 0 | 0 | 2 | 0 | 29 |
| | Finland | 0 | 4 | 1 | 0 | 0 | 2 | 1 | 3 | 0 | 0 | 2 | 0 | 13 |
| | Latvia | 5 | 2 | 0 | 1 | 41 | 0 | 4 | 1 | 0 | 0 | 2 | 0 | 56 |
| | Lithuania | 1 | 3 | 0 | 1 | 2 | 2 | 0 | 0 | 0 | 0 | 1 | 0 | 10 |
| | Norway | 0 | 0 | 0 | 1 | 1 | 2 | 1 | 0 | 0 | 0 | 0 | 0 | 5 |
| | Sweden | 0 | 0 | 0 | 0 | 1 | 3 | 3 | 0 | 0 | 0 | 0 | 0 | 7 |
| | **Total** | **10** | **19** | **1** | **3** | **49** | **11** | **15** | **5** | **0** | **0** | **7** | **0** | **120** |
| **Southern Europe** | Italy | 2 | 1 | 0 | 5 | 0 | 2 | 2 | 0 | 4 | 0 | 1 | 0 | 17 |
| | Portugal | 1 | 3 | 0 | 6 | 0 | 0 | 6 | 1 | 0 | 1 | 1 | 0 | 19 |
| | Turkey | 0 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 |
| | **Total** | **3** | **8** | **0** | **11** | **0** | **2** | **8** | **1** | **4** | **1** | **2** | **0** | **40** |
| **Western Europe** | Belgium Flanders | 4 | 1 | 0 | 0 | 0 | 4 | 3 | 0 | 0 | 0 | 1 | 0 | 13 |
| | Belgium Wallonia | 2 | 11 | 0 | 0 | 1 | 4 | 3 | 0 | 0 | 2 | 1 | 2 | 26 |
| | France | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 5 |
| | Ireland | 2 | 2 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 7 |
| | The Netherlands | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 14 | 33 |
| | United Kingdom | 1 | 5 | 1 | 2 | 2 | 0 | 2 | 4 | 1 | 0 | 1 | 0 | 19 |
| | **Total** | **10** | **20** | **3** | **3** | **4** | **9** | **8** | **5** | **1** | **2** | **3** | **16** | **103** |
| | **Total (all regions)** | **43** | **161** | **5** | **37** | **266** | **68** | **37** | **40** | **10** | **6** | **66** | **89** | **791** |

**Table 2***:* Number of researchers interviewed for the three specific topics within the EJP SOIL conceptual framework (Munkholm et al. 2021).

| | | Carbon stocks | | | Soil degradation and fertility | | | Strategies for improved soil management | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | University | National research institutes | Non-governmental research organizations | University | National research institutes | Non-governmental research organizations | University | National research institutes | Non-governmental research organizations | Total |
| **Central Europe** | Austria | 0 | 1 | 0 | 2 | 1 | 0 | 1 | 0 | 0 | 5 |
| | Czechia | 5 | 2 | 0 | 7 | 2 | 0 | 4 | 2 | 0 | 22 |
| | Germany | 2 | 2 | 0 | 1 | 2 | 0 | 2 | 3 | 0 | 12 |
| | Hungary | 2 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 17 |
| | Poland | 3 | 5 | 0 | 3 | 5 | 0 | 3 | 5 | 0 | 24 |
| | Slovakia | 0 | 6 | 0 | 0 | 7 | 0 | 3 | 11 | 0 | 27 |
| | Slovenia | 3 | 2 | 0 | 6 | 1 | 0 | 2 | 1 | 0 | 15 |
| | Switzerland | 0 | 1 | 0 | 0 | 9 | 0 | 0 | 9 | 0 | 19 |
| | **Total** | **15** | **21** | **1** | **21** | **29** | **2** | **17** | **33** | **2** | **141** |
| **Northern Europe** | Denmark | 3 | 1 | 0 | 9 | 1 | 0 | 9 | 1 | 0 | 24 |
| | Finland | 2 | 2 | 0 | 2 | 2 | 0 | 2 | 2 | 0 | 12 |
| | Latvia | 3 | 5 | 2 | 3 | 5 | 2 | 3 | 5 | 2 | 30 |
| | Lithuania | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 9 |
| | Norway | 0 | 0 | 1 | 1 | 1 | 2 | 1 | 1 | 2 | 9 |
| | Sweden | 2 | 0 | 1 | 1 | 0 | 1 | 2 | 0 | 2 | 9 |
| | **Total** | **11** | **9** | **5** | **17** | **10** | **6** | **18** | **10** | **7** | **93** |
| **Southern Europe** | Italy | 6 | 1 | 0 | 6 | 1 | 0 | 6 | 1 | 0 | 21 |
| | Spain | 6 | 10 | 0 | 7 | 10 | 0 | 7 | 7 | 0 | 47 |
| | Portugal | 7 | 0 | 0 | 13 | 0 | 0 | 13 | 1 | 0 | 34 |
| | Turkey | 3 | 5 | 1 | 3 | 5 | 1 | 3 | 5 | 1 | 27 |
| | **Total** | **22** | **16** | **1** | **29** | **16** | **1** | **29** | **14** | **1** | **129** |
| **Western Europe** | Belgium Flanders | 4 | 9 | 8 | 5 | 10 | 9 | 5 | 10 | 9 | 69 |
| | Belgium Wallonia | 3 | 1 | 0 | 5 | 1 | 0 | 3 | 3 | 1 | 17 |
| | France | 0 | 6 | 1 | 0 | 10 | 1 | 0 | 4 | 1 | 23 |
| | Ireland | 0 | 4 | 0 | 0 | 4 | 0 | 0 | 4 | 0 | 12 |
| | The Netherlands | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 18 |
| | United Kingdom | 2 | 3 | 0 | 2 | 3 | 0 | 2 | 3 | 0 | 15 |
| | **Total** | **11** | **25** | **11** | **14** | **30** | **12** | **12** | **26** | **13** | **154** |
| | **Total (all regions)** | **59** | **71** | **18** | **81** | **85** | **21** | **76** | **83** | **23** | **517** |

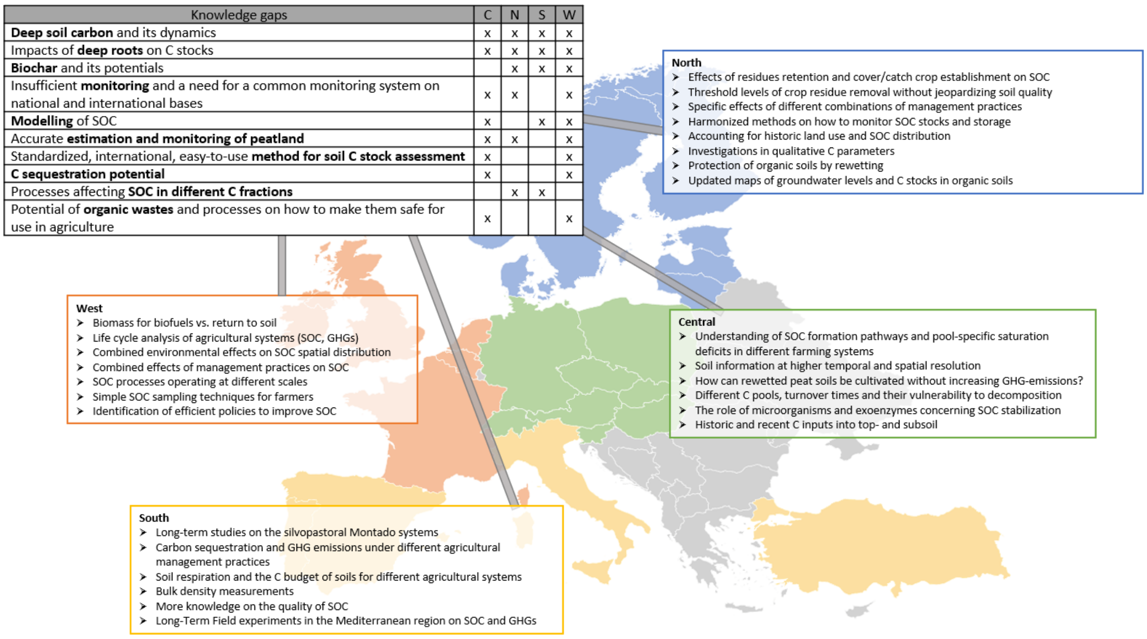


**Figure 1:** The most critical knowledge gaps identified by researchers with respect to ´soil carbon stocks` stated across the four regions. The table in the upper left corner presents the ten main knowledge gaps on carbon stocks and their prevalence in the national reports, although not ranked in order of importance. The detailed list for each of the four regions present specific knowledge gaps for each region (adapted from Munkholm et al. (2021)).

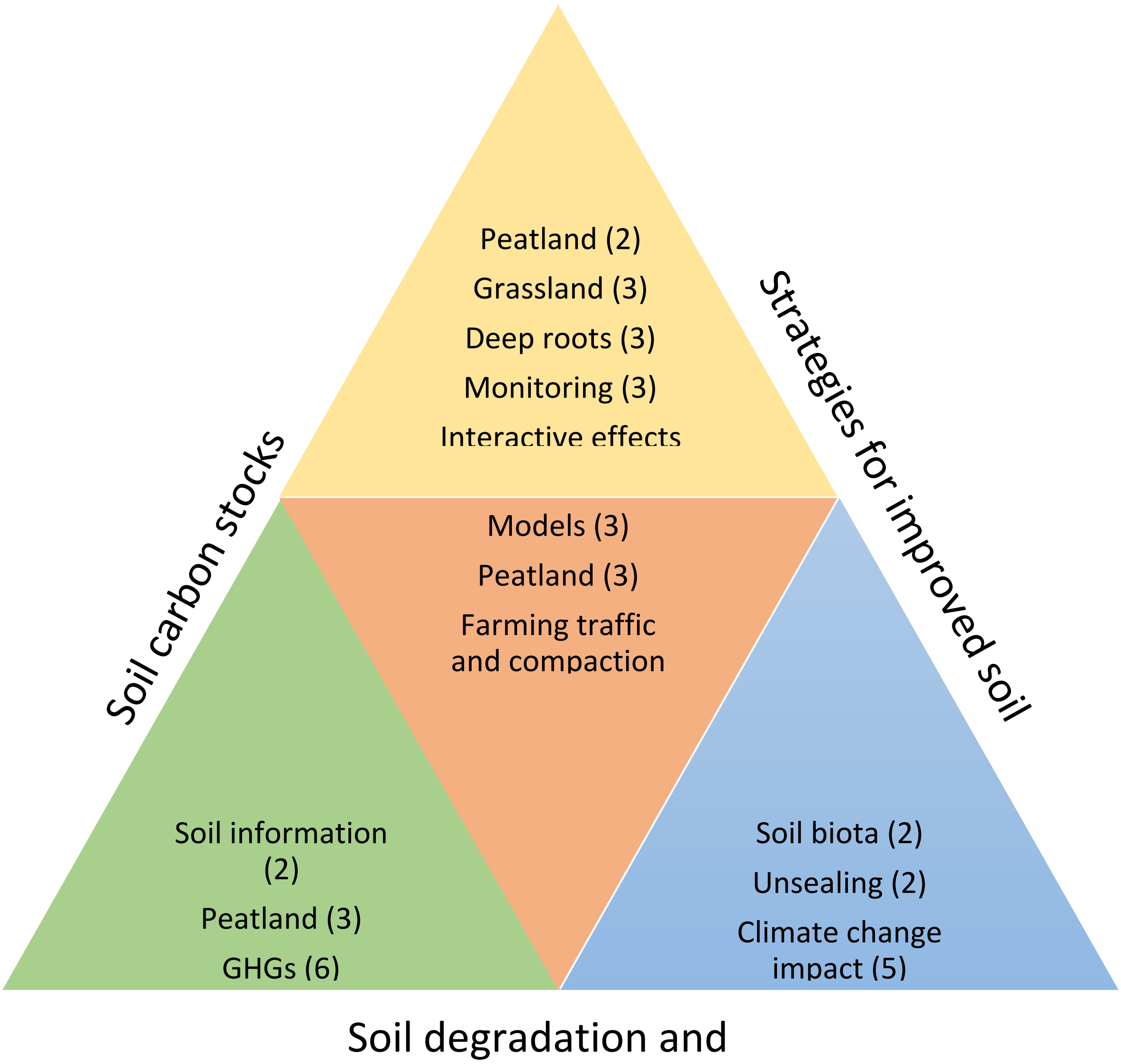


**Figure 2.** Overlapping knowledge gaps found in the three different topics (numbers in brackets indicate number of national reports mentioning overlapping knowledge gaps). The sides of the large triangle represent the three topics addressed by researchers, the corner triangles show overlapping knowledge 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'. Source: Munkholm et al. (2021).

**Table 3:** Identification of the most pressing research gaps. This table overlays two questions from the assessment 1) "How important are the following challenges to sustainable soil management" and 2) "How important are research gaps for the following soil challenges?" Thereby identifying stakeholders' perception of the most important soil challenges with the most pressing gaps in research gaps (Thorsøe, 2021).

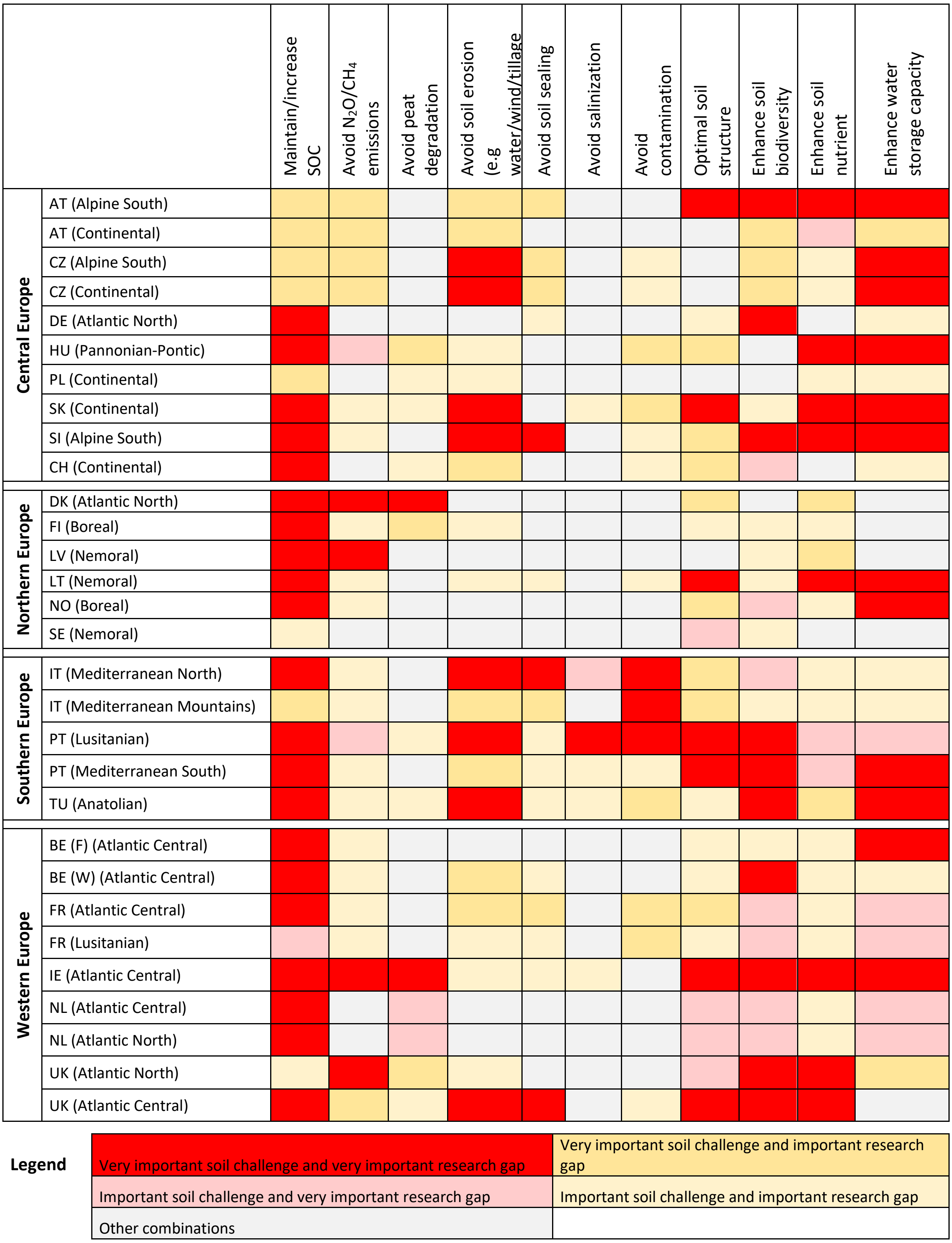

**Table 4:** Replies to three questions regarding the strength of the knowledge system in the countries (Thorsøe, 2021).

| | To which extent is the current knowledge system sufficiently effective in communicating knowledge on sustainable soil management to farmers? | To which extent are sufficient resources available for the dissemination of knowledge on sustainable soil management? | To which extent are sufficient financial resources available for the production of knowledge on sustainable soil management? |
|---|---|---|---|
| Austria | | | |
| Belgium Flanders | | | |
| Belgium Wallonia | | | |
| Czechia | | | |
| Denmark | | | |
| Finland | | | |
| France | | | |
| Germany | | | |
| Hungary | | | |
| Ireland | | | |
| Italy | | | |
| Latvia | | | |
| Lithuania | | | |
| Norway | | | |
| Poland | | | |
| Portugal | | | |
| Slovakia | | | |
| Slovenia | | | |
| Sweden | | | |
| Switzerland | | | |
| The Netherlands | | | |
| Turkey | | | |
| United Kingdom | | | |

| **Legend** | Very important | Important | Neutral | Less important | Not important at all |
|---|---|---|---|---|---|

**Table 5:** Stakeholders' replies to the question: "How important are the following undertakings to improve soil knowledge in this environmental zone?" (Thorsøe, 2021).

| | | New scientific knowledge on the prevalence of key soil challenges | New management strategies for sustainable soil management | Improve soil monitoring | Increase availability of existing research for stakeholders | Increase availability of existing research for policymakers | Improve the coordination of knowledge production | Other |
|---|---|---|---|---|---|---|---|---|
| **Central Europe** | AT (Alpine South) | Important | Important | Important | Very important | Very important | Very important | Very important |
| | AT (Continental) | Important | Important | Very important | Very important | Important | Very important | Neutral |
| | CZ (Alpine South) | Very important | Very important | Less important | Important | Important | Very important | Neutral |
| | CZ (Continental) | Very important | Very important | Less important | Important | Important | Very important | Neutral |
| | DE (Atlantic North) | Neutral | Important | Neutral | Very important | Neutral | Very important | Very important |
| | HU (Pannonian-Pontic) | Important | Very important | Very important | Very important | Very important | Very important | Neutral |
| | PL (Continental) | Important | Very important | Important | Important | Neutral | Very important | Not important at all |
| | SK (Continental) | Very important | Very important | Very important | Important | Very important | Very important | Very important |
| | SI (Alpine South) | Important | Very important | Important | Very important | Important | Very important | Very important |
| | CH (Continental) | Important | Very important | Important | Very important | Important | Very important | Very important |
| **Northern Europe** | DK (Atlantic North) | Important | Very important | Important | Very important | Important | Neutral | Neutral |
| | FI (Boreal) | Very important | Very important | Important | Important | Important | Important | Neutral |
| | LV (Nemoral) | Very important | Very important | Very important | Very important | Very important | Very important | Neutral |
| | LT (Nemoral) | Very important | Very important | Very important | Very important | Very important | Very important | Less important |
| | NO (Boreal) | Very important | Very important | Very important | Very important | Very important | Very important | Very important |
| | SE (Nemoral) | Important | Important | Neutral | Very important | Important | Neutral | Neutral |
| **Southern Europe** | IT (Mediterranean North) | Important | Important | Very important | Important | Very important | Very important | Important |
| | IT (Mediterranean Mountains) | Important | Very important | Very important | Important | Very important | Very important | Important |
| | PT (Lusitanian) | Important | Very important | Very important | Very important | Very important | Very important | Neutral |
| | PT (Mediterranean South) | Important | Very important | Very important | Very important | Very important | Very important | Neutral |
| | TU (Anatolian) | Very important | Very important | Very important | Very important | Very important | Very important | Not important at all |
| **Western Europe** | BE (F) (Atlantic Central) | Very important | Important | Important | Important | Important | Very important | Neutral |
| | BE (W) (Atlantic Central) | Important | Very important | Important | Very important | Very important | Very important | Neutral |
| | FR (Atlantic Central) | Important | Important | Very important | Very important | Important | Important | Not important at all |
| | FR (Lusitanian) | Important | Important | Very important | Very important | Very important | Important | Not important at all |
| | IE (Atlantic Central) | Very important | Very important | Important | Very important | Important | Very important | Neutral |
| | NL (Atlantic Central) | Important | Important | Very important | Very important | Important | Important | Important |
| | NL (Atlantic North) | Important | Important | Very important | Very important | Important | Important | Important |
| | UK (Atlantic North) | Important | Important | Important | Important | Important | Very important | Less important |
| | UK (Atlantic Central) | Very important | Important | Very important | Important | Important | Very important | Less important |

| **Legend** | | | | | |
|---|---|---|---|---|---|
| | Very important | Important | Neutral | Less important | Not important at all |

## Contributor Roles

Here please list your name and in parenthesis indicate your role in writing the paper according to the Contributor Roles Taxonomy (CRediT) (Conceptualization; Data curation; Formal Analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Writing – original draft; Writing – review & editing)

1. Martin Hvarregaard Thorsøe (Conceptualization; Methodology; Writing – original draft; Writing – review & editing).
2. Saskia Keestra (Writing - reviewing & editing)
3. Maarten De Boever (Writing - reviewing & editing)
4. Kristina Buchová (Writing - reviewing & editing)
5. Frederik Bøe (Writing - reviewing & editing; data collection and reporting for Norway)
6. Nádia Castanheira (Writing - reviewing & editing; data collection and reporting for Portugal)
7. Claire Chenu (Writing - reviewing & editing)
8. Sophie Cornu (Writing-reviewing & editing, data collection and reporting for France)
9. Axel Don (Writing - reviewing & editing and reporting for Germany)
10. Julia Fohrafellner (Data curation; Formal Analysis; Visualization; Writing - review & editing; data collection and reporting for Austria)
11. Roberta Farina (Writing – review & editing)
12. Dario Fornara (Writing - reviewing & editing; data collection and reporting for the UK)
13. Maria Gonçalves (Writing - reviewing & editing; data collection and reporting for Portugal)
14. Morten Graversgaard (Writing - reviewing & editing)
15. Olivier Heller (Writing - reviewing & editing)
16. Erich Inselsbacher (Writing - reviewing & editing)
17. Anna Jacobs (Writing-reviewing & editing, data collection and reporting for Germany)
18. Sara Mavsar (Writing - reviewing & editing; data collection and reporting for Slovenia)
19. Katharina H. E. Meurer (Writing - review & editing; data collection and reporting for Sweden)
20. Rok Mihelič (Writing - reviewing & editing; data collection and reporting for Slovenia)
21. Lilian O'Sullivan (Writing - reviewing & editing; data collection and reporting for Ireland)
22. Mansonia Pulido-Moncada (Methodology, Knowledge gap analysis, writing, reviewing and editing, coordination of EU data evaluation on soil carbon stocks, data collection and reporting for DK)
23. Greet Ruysschaert (Writing-reviewing & editing, data collection and reporting for Belgium-Flanders)
24. Michal Sviček (Writing - reviewing & editing; data collection and reporting for Slovakia)
25. Mika Tähtikarhu (Writing - reviewing & editing; data collection and reporting for Finland)

26. Silvia Vanino (Writing - reviewing & editing; data collection and reporting for Italy).
27. Wieke Vervuurt (Writing - reviewing & editing; data collection and reporting for the Netherlands)
28. Sophie Zechmeister-Boltenstern (Knowledge gap analysis, Figure 1 and Figure 2, writing, reviewing and editing, coordination of EU data evaluation on soil carbon stocks, national coordination of Austrian contributions)
29. Lars J. Munkholm (Conceptualization, methodology, knowledge gap analysis, writing - reviewing & editing)

# Acknowledgments

This work was funded under the European Joint Program for SOIL (EJP SOIL), which has received funding from the European Union's Horizon 2020 research and innovation programme: Grant agreement No 862695.

The authors would like to thank all the stakeholders who have taken their time to take part in the interviews which form the basis of the work in the article.

Noemi Peter - data collection and reporting for Switzerland

Julia Miloczki - data collection and reporting for Austria

Martina Kasper - data collection and reporting for Austria

Eloise Mason - data collection and reporting for France

# References

Alrøe, H. F., & Noe, E. (2014). Second-order science of interdisciplinary research: A polyocular framework for wicked problems. *Constructivist Foundations, 10*(1), 65-95.

Beaudoin, C., Joncoux, S., Jasmin, J.-F., Berberi, A., McPhee, C., Schillo, R. S., & Nguyen, V. M. (2022). A research agenda for evaluating living labs as an open innovation model for environmental and agricultural sustainability. *Environmental Challenges, 7*, 100505. doi:https://doi.org/10.1016/j.envc.2022.100505

Bouma, J., de Haan, J., & Dekkers, M.-F. S. (2022). Exploring Operational Procedures to Assess Ecosystem Services at Farm Level, including the Role of Soil Health. *Soil Systems, 6*(2), 34. Retrieved from https://www.mdpi.com/2571-8789/6/2/34

Bouma, J., & McBratney, A. (2013). Framing soils as an actor when dealing with wicked environmental problems. *Geoderma, 200*, 130-139.

Brady, M. V., Andersen, M. S., Andersson, A., Kilis, E., Saarela, S.-R., & Hvarregaard Thorsøe, M. (2022). Strengthening the policy framework to resolve lax implementation of the Baltic Sea Action Plan for agriculture. *Ambio, 51*(1), 69-83.

Corbin, J. M. (1998). *Basics of qualitative research : techniques and procedures for developing grounded theory* (2. ed. ed.). Thousand Oaks, USA: SAGE.

Creswell, J. W. (2014). *Research design : qualitative, quantitative, and mixed methods approaches* (Fourth edition, international student edition ed.). Los Angeles, Calif.: SAGE.

Dalkir, K. (2005). The knowledge management cycle. *Knowledge management in theory and practice. Oxford: Elsevier*, 25-46.

DeCaro, D. A., Chaffin, B. C., Schlager, E., Garmestani, A. S., & Ruhl, J. (2017). Legal and institutional foundations of adaptive environmental governance. *Ecology and society: A journal of integrative science for resilience and sustainability, 22*(1), 1.

EC. (2021). *EU Soil Strategy for 2030 : Reaping the benefits of healthy soils for people, food, nature and climate*. Retrieved from Brussels, Belgium: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52021DC0699&from=EN

EC. (2022). EU Mission: A Soil Deal for Europe. Retrieved from https://ec.europa.eu/info/research-and-innovation/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/eu-missions-horizon-europe/soil-health-and-food_en

ECA. (2021). *Special report 16/2021: Common Agricultural Policy and Climate : Half of EU Climate Spending but Farm Emissions Are Not Decreasing*. Retrieved from Brussels, Belgium: https://www.eca.europa.eu/en/Pages/DocItem.aspx?did=58913

FAO. (2015a). *Revised World Soil Charter*. Retrieved from Rome, Italy: https://www.fao.org/documents/card/en/c/e60df30b-0269-4247-a15f-db564161fee0/

FAO. (2015b). *Status of the World's Soil Resources: Main Report*. Retrieved from Rome, Italy: https://www.fao.org/documents/card/en/c/c6814873-efc3-41db-b7d3-2081a10ede50/

Ferreira, C. S., Seifollahi-Aghmiuni, S., Destouni, G., Ghajarnia, N., & Kalantari, Z. (2022). Soil degradation in the European Mediterranean region: Processes, status and consequences. *Science of the Total Environment, 805*, 150106.

Folke, C., Hahn, T., Olsson, P., & Norberg, J. (2005). Adaptive governance of social-ecological systems. *Annu. Rev. Environ. Resour., 30*, 441-473.

Frelih-Larsen, A. I., S.; Herb, I , Tarpey, J.;.Olesen, E.J.; Graversgaard, M.; Claessens, L.; Emoke; Madari, B.; Razafimbelo, T.; Kontoboytseva, A.; Nciizah, A.; Swanepoel, C.; Katto, C.; Verchot, L.; Baldock, J.; Grundy, M.; Hongmin, D.; Li, Y.; McNeill, S.; Arias-Navarro, C.; Soussana, J., F.; Tran, T. M.; Jouqet, P.; Demenois, J. . (2017). Deliverable D2.3 Synthesis report on knowledge demands and needs of stakeholders. *CIRCASA project*. Retrieved from https://www.circasa-project.eu/content/download/4156/39989/version/1/file/CIRCASA_D2.3_Synthesis%20report%20on%20knowledge%20demands%20and%20needs%20of%20stakeholders%20%282%29.pdf

Hessel, R., Wyseure, G., Panagea, I. S., Alaoui, A., Reed, M. S., van Delden, H., . . . Chivers, C.-A. (2022). Soil-Improving Cropping Systems for Sustainable and Profitable Farming in Europe. *Land, 11*(6), 780. Retrieved from https://www.mdpi.com/2073-445X/11/6/780

Heuser, D. I. (2022). Soil Governance in current European Union Law and in the European Green Deal. *Soil Security, 6*, 100053. doi:https://doi.org/10.1016/j.soisec.2022.100053

Huber-Stearns, H. R., Bennett, D. E., Posner, S., Richards, R. C., Fair, J. H., Cousins, S. J. M., & Romulo, C. L. (2017). Social-ecological enabling conditions for payments for ecosystem services. *Ecology and Society, 22*(1). Retrieved from http://www.jstor.org/stable/26270112

Ingram, J., & Mills, J. (2019). Are advisory services "fit for purpose" to support sustainable soil management? An assessment of advice in Europe. *Soil Use and Management, 35*(1), 21-31.

Ingram, J., Mills, J., Black, J. E., Chivers, C.-A., Aznar-Sánchez, J. A., Elsen, A., . . . Skaalsveen, K. (2022). Do agricultural advisory services in Europe have the capacity to support the transition to healthy soils? *Land, 11*(5), 599.

IPBES. (2018). *Assessment Report on Land Degradation and Restoration*. Retrieved from Bonn, Germany. : https://ipbes.net/assessment-reports/ldr

Keesstra, S., Chenu, C., Munkholm, L. J., Cornu, S., Kuikman, P. J., Thorsøe, M. H., . . . Visser, S. M. ((in review)). The road towards climate smart and sustainable agricultural soil management: knowledge needs and new research approaches. *European Journal of Soil Science*.

Keesstra, S., Mol, G., De Leeuw, J., Okx, J., Molenaar, C., De Cleen, M., & Visser, S. (2018). Soil-Related Sustainable Development Goals: Four Concepts to Make Land Degradation Neutrality and Restoration Work. *Land, 7*(4), 133. Retrieved from https://www.mdpi.com/2073-445X/7/4/133

Klerkx, L. (2020). Advisory services and transformation, plurality and disruption of agriculture and food systems: towards a new research agenda for agricultural education and extension

studies. *The Journal of Agricultural Education and Extension, 26*(2), 131-140. doi:10.1080/1389224X.2020.1738046
Klerkx, L., & Leeuwis, C. (2009). Establishment and embedding of innovation brokers at different innovation system levels: Insights from the Dutch agricultural sector. *Technological forecasting and social change, 76*(6), 849-860.
Klerkx, L., van Mierlo, B., & Leeuwis, C. (2012). Evolution of systems approaches to agricultural innovation: concepts, analysis and interventions. In I. Darnhofer, D. Gibbon, & B. Dedieu (Eds.), *Farming Systems Research into the 21st century: The New Dynamic* (pp. 457-483). New York: Springer.
Knierim, A., Boenning, K., Caggiano, M., Cristóvão, A., Dirimanova, V., Koehnen, T., . . . Prager, K. (2015). The AKIS Concept and its Relevance in Selected EU Member States. *Outlook on agriculture, 44*(1), 29-36. doi:10.5367/oa.2015.0194
Labarthe, P., & Beck, M. (2022). CAP and Advisory Services: From Farm Advisory Systems to Innovation Support. *EuroChoices, 21*(1), 5-14. doi:https://doi.org/10.1111/1746-692X.12354
Madureira, L., Labarthe, P., Marques, C. S., & Santos, G. (2022). Exploring microAKIS: farmer-centric evidence on the role of advice in agricultural innovation in Europe. *The Journal of Agricultural Education and Extension, 28*(5), 549-575. doi:10.1080/1389224X.2022.2123838
Markard, J., Geels, F. W., & Raven, R. (2020). Challenges in the acceleration of sustainability transitions. *Environmental Research Letters, 15*(8), 081001.
McDonald, H., Frelih-Larsen, A., Keenleyside, C., Lóránt, A., Duin, L., Andersen, S. P., . . . Hiller, N. (2021). Carbon farming, Making agriculture fit for 2030.
McPhee, C., Bancerz, M., Mambrini-Doudet, M., Chrétien, F., Huyghe, C., & Gracia-Garza, J. (2021). The defining characteristics of agroecosystem living Labs. *Sustainability, 13*(4), 1718.
Metzger, M. J., Bunce, R. G. H., Jongman, R. H. G., Mücher, C. A., & Watkins, J. W. (2005). A climatic stratification of the environment of Europe. *Global Ecology and Biogeography, 14*(6), 549-563. doi:https://doi.org/10.1111/j.1466-822X.2005.00190.x
Munkholm, L. J., Zechmeister-Boltenstern, S., Taghizadeh-Toosi, A., Knadel, M., Nørgaard, T., Arthur, E., . . . Kasper, M. (2021). *Deliverable D2.6 Set of reports on State of knowledge in agricultural soil management*. Retrieved from https://ejpsoil.eu/fileadmin/projects/ejpsoil/WP2/Deliverable_D2.6_Set_of_reports_on_State_of_knowledge_in_agricultural_soil_management.pdf
Orgiazzi, A., Ballabio, C., Panagos, P., Jones, A., & Fernández-Ugalde, O. (2018). LUCAS Soil, the largest expandable soil dataset for Europe: a review. *European Journal of Soil Science, 69*(1), 140-153. doi:https://doi.org/10.1111/ejss.12499
Petrescu-Mag, R. M., Petrescu, D. C., & Azadi, H. (2020). A social perspective on soil functions and quality improvement: Romanian farmers' perceptions. *Geoderma, 380*, 114573. doi:https://doi.org/10.1016/j.geoderma.2020.114573
Potokar, M. Č., Tomažin, U., & Škrlep, M. (2021). D1. 4. Report on Available Multi-Actor (MA) Project Data–Best Practices European Knowledge Repository for Best Agricultural Practices. *EUREKA*, 1-109.
Reed, M. S. (2008). Stakeholder participation for environmental management: A literature review. *Biological Conservation, 141*(10), 2417-2431. doi:10.1016/j.biocon.2008.07.014
Ristić, R., Solomun, M. K., Malušević, I., Ždrale, S., Radić, B., Polovina, S., & Milćanović, V. (2020). Healthy Soils—Healthy People: Soil and Human Health—The Reality of the Balkan Region. In *The Soil–Human Health Nexus* (pp. 223-248): CRC Press.
Rust, N., Ptak, E., Graversgaard, M., Iversen, S., Reed, M., de Vries, J., . . . Dalgaard, T. (2020). Social capital factors affecting uptake of sustainable soil management practices: a literature review. *Emerald Open Research, 2*(8). doi:10.35241/emeraldopenres.13412.2
Schismenos, S., Emmanouloudis, D., Stevens, G. J., Katopodes, N. D., & Melesse, A. M. (2022). Soil governance in Greece: A snapshot. *Soil Security, 6*, 100035. doi:https://doi.org/10.1016/j.soisec.2022.100035

Silverman, D. (2011). *Interpreting qualitative data : a guide to the principles of qualitative research* (4. ed. ed.). London, UK: SAGE.
Strauss, V., Paul, C., Dönmez, C., Löbmann, M., & Helming, K. (2023). Sustainable soil management measures: a synthesis of stakeholder recommendations. *Agronomy for Sustainable Development, 43*(1), 17.
Tanneberger, F., Moen, A., Barthelmes, A., Lewis, E., Miles, L., Sirin, A., . . . Joosten, H. (2021). Mires in Europe—Regional Diversity, Condition and Protection. *Diversity, 13*(8), 381. Retrieved from https://www.mdpi.com/1424-2818/13/8/381
Thorsøe, M. H. (2021). Deliverable 2.7 : Report on the current availability and use of soil knowledge. Retrieved from https://ejpsoil.eu/fileadmin/projects/ejpsoil/WP2/Deliverable_2.7_Report_on_the_current_availability_and_use_of_soil_knowledge.pdf
Thorsøe, M. H., Andersen, M. S., Brady, M. V., Graversgaard, M., Kilis, E., Pedersen, A. B., . . . Valve, H. (2022). Promise and performance of agricultural nutrient management policy: Lessons from the Baltic Sea. *Ambio, 51*(1), 36-50.
Thorsøe, M. H., Noe, E. B., Lamandé, M., Frelih-Larsen, A., Kjeldsen, C., Zandersen, M., & Schjønning, P. (2019). Sustainable soil management - Farmers' perspectives on subsoil compaction and the opportunities and barriers for intervention. *Land Use Policy, 86*, 427-437. doi:https://doi.org/10.1016/j.landusepol.2019.05.017
van Leeuwen, J. P., Saby, N., Jones, A., Louwagie, G., Micheli, E., Rutgers, M., . . . Creamer, R. (2017). Gap assessment in current soil monitoring networks across Europe for measuring soil functions. *Environmental Research Letters, 12*(12), 124007.
Vanino, S., Pirelli, T., Di Bene, C., Bøe, F., Castanheira, N., Chenu, C., . . . Farina, R. (2023). Barriers and opportunities of soil knowledge to address soil challenges: Stakeholders' perspectives across Europe. *Journal of Environmental Management, 325, Part B*, 116581. doi:https://doi.org/10.1016/j.jenvman.2022.116581
Veerman, C., Pinto Correia, T., Bastioli, C., Biro, B., Bouma, J., Cienciala, E., . . . Wittkowski, R. (2020). *Caring for soil is caring for life : ensure 75% of soils are healthy by 2030 for healthy food, people, nature and climate : interim report of the mission board for soil health and food*. Brussels, Belgium: European Commission : Directorate-General for Research and Innovation.
Visser, S., Keesstra, S., Maas, G., De Cleen, M., & Molenaar, C. (2019). Soil as a basis to create enabling conditions for transitions towards sustainable land management as a key to achieve the SDGs by 2030. *Sustainability, 11*(23), 6792.