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Sustainable soil management: Soil knowledge use and gaps in Europe

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67 **Abstract:**

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

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

91 Highlights

92 1. Assessment of state of knowledge concerning sustainable soil management in Europe

93 2. Knowledge on stakeholder needs and soil processes is crucial to improve soil management

94 3. Key knowledge gaps: SOC loss and dynamics, peatland degradation, soil compaction and on
95 improving models and availability of input data

96 4. Insufficient research transfer to practitioners hinders adoption of sustainable soil
97 management

98

99 1. Introduction

100 Soils are the foundation of agriculture and provide crucial ecosystem services, including the
101 production of food and bioenergy crops, feed, fibers, the regulation of groundwater, as well as
102 contributing to resilient agroecosystems associated with soil biodiversity (Bouma & McBratney,
103 2013). Current intensive farming practices have exposed agricultural soils to a range of negative
104 effects including loss of soil organic carbon (SOC), soil erosion and nutrient leaching, with
105 implications that go beyond the farmland area (FAO, 2015b; IPBES, 2018). The European Commission
106 (EC) assessed that as much as 60-70% of European soils are degraded as a direct result of
107 unsustainable agricultural management practices and soils have lost significant capacity to provide
108 ecosystem services (Veerman et al., 2020). However, soil health status across different geographical
109 areas and in relation to specific soil threats remains uncertain (Ferreira, Seifollahi-Aghmiuni,
110 Destouni, Ghajarnia, & Kalantari, 2022).

111 There are several policies and legal instruments that refer to soil threats and soil knowledge
112 production. Moreover, soil policy ambitions recently increased at European level, as reflected in the
113 soil strategy, the Nature Restoration Law as well as the proposal for a Soil Health Law (EC, 2021).
114 Although neglected for years, the protection of soils has recently become an important item on the
115 political agenda, particularly in relation to the size of soil carbon pools, which can contribute to
116 mitigating climate change and achieving the ambitions laid out in the European Green Deal (Heuser,
117 2022; Visser, Keesstra, Maas, De Cleen, & Molenaar, 2019). In response, the European Union (EU)
118 has adopted a Soil Strategy for the EU, which seeks to achieve healthy soils by 2050 based on a
119 framework and concrete measures to protect and restore soils, and to ensure their sustainable use
120 (EC, 2021). In addition, the EC has launched the Mission 'A Soil Deal for Europe', which will support
121 the transition towards healthy soils by 2030 through a series of research and intervention actions
122 (EC, 2022).

123 In the EU Soil strategy, sustainable soil management is emphasized as the way to prevent
124 degradation and restore unhealthy soils (EC, 2021). Sustainable soil management encompasses a set
125 of practices that are able to maintain the soil in, or restore it to, a healthy condition yielding multiple
126 benefits, including for water and air. These practices increase soil biodiversity, fertility and resilience
127 which are needed for the vitality of rural areas. However, soil management is complex, since a series
128 of soil physical, biological and chemical processes must be accounted for, and soils and soil
129 properties are diverse across different scales. Furthermore, soil management is connected with a
130 range of aspects like different land-uses, pedo-climatic conditions, access to inputs, machinery,
131 technology, multiple public policies and socio-cultural values (Hessel et al., 2022; Ingram & Mills,
132 2019; Thorsøe et al., 2019). According to the World Soil Charter, soil management is sustainable if
133 the supporting, provisioning, regulating, and cultural services provided by the soil are maintained or
134 enhanced without significantly impairing either the soil functions that enable those services or
135 biodiversity (FAO, 2015a). However, soil management decisions often involve trade-offs between
136 mutually excluding outcomes such as mitigation of greenhouse gas (GHG) emissions, yield
137 optimization, biodiversity protection and a range of other important ecosystem services. Moreover,
138 pedo-climatic conditions diverge substantially across Europe and it is important to tailor solutions to
139 these conditions and the specific challenges that prevail (Hessel et al., 2022).

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

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

155 The systematic and deliberate management of knowledge among key actors is an important aspect
156 of the AKIS in most European countries (Klerkx et al., 2012; Knierim et al., 2015; Labarthe & Beck,
157 2022). Knowledge management includes important aspects like knowledge production, where
158 knowledge is captured or created, knowledge transfer whereby knowledge is translated and made
159 available to practitioners as well as knowledge use, where practitioners adopt knowledge and
160 change their farming practice (Dalkir, 2005). Within the agri-food sector, various groups of actors are
161 involved in these processes, while knowledge production typically takes place in specialized
162 institutions such as universities or research centres, knowledge transfer is facilitated by knowledge
163 brokers such as the advisory services and finally knowledge is used by farmers or related end users.
164 Within the agri-food sector, public funding facilitates knowledge production, transfer and use in
165 support of policy objectives and to assess and develop effective policies. Ensuring alignment across
166 these three arenas is therefore an important aspect of knowledge management (Dalkir, 2005; Klerkx
167 & Leeuwis, 2009).

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

172 Although soil data is available at European scale (see for instance Orgiazzi, Ballabio, Panagos, Jones,
173 and Fernández-Ugalde (2018)), there are also substantial gaps in European soil knowledge. With
174 respect to available soil monitoring, van Leeuwen et al. (2017) found that biological and physical
175 attributes were severely under-represented vis a vis chemical parameters. Existing stocktakes of
176 knowledge availability found that research output is generally published in line with the FAIR
177 principles (Findable, Accessible, Interoperable, Reusable) (Potokar, Tomažin, & Škrlep, 2021).
178 However, often these findings are neither directly applicable to practitioners nor are the underlying
179 data or models (Hessel et al., 2022; Labarthe & Beck, 2022; Potokar et al., 2021). Regarding
180 knowledge use in farming, further implementation barriers are complex and involve fragmentation
181 of advisory services as well as lacking end users' capacities (Ingram & Mills, 2019; Ingram et al.,
182 2022). With respect to SOC, Frelih-Larsen (2017) in a stakeholder consultation find that knowledge
183 gaps are particularly about farm-level management practices, their effects, economic costs and
184 benefits. In sum, existing studies of the European AKIS indicate that gaps in knowledge availability
185 and use are complex and regionally diverse, hence to effectively address insufficiencies a thorough
186 analysis is needed.

187 Against this background, the objective of this article is to assess the state of knowledge, knowledge
188 use and knowledge gaps concerning sustainable soil management in Europe. This assessment is
189 based on inputs from an extensive public consultation among a broad stakeholder group and a
190 group of soil researchers from across Europe. With this approach, we move beyond an assessment

191 of the knowledge gaps from an academic perspective and also discuss opportunities to address
192 these knowledge gaps from a practice and policy perspective. Thus, this supplements already
193 existing assessments of soil challenges (FAO, 2015b; Ferreira et al., 2022; Vanino et al., 2023;
194 Veerman et al., 2020). Further, the synthesis presented here also extends the findings originally
195 presented under the EJP SOIL programme, by providing additional data analysis and aligning with the
196 existing academic literature on soil knowledge use and knowledge gaps.

197 2. Materials and methods

198 The data that constitute the basis of this article were acquired with two assessments that were
199 completed in the spring of 2020 to develop a roadmap for EU Agricultural Soil Management research
200 within the European Joint Programme on soil (EJP SOIL). EJP SOIL is a research programme on
201 agricultural soil management (2020-2025) co-funded by the EC and the participating European
202 countries (24 in total). EJP SOIL contributes to develop knowledge, tools and an integrated research
203 community to foster climate-smart sustainable agricultural soil management. In each partner
204 country, a broad group of soil stakeholders was formed, the so-called National Hubs, to inquire
205 about their perspectives on various agricultural soil related topics (for more information please see
206 www.ejpsoil.eu). The present article is a synthesis of two sets of 23 national reports prepared by
207 each partner, based on a series of interviews with the broad group of stakeholders in the National
208 Hubs and a consultation of key researchers at national level.

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

215 In this article, the Northern region is represented by Denmark (DK), Estonia (EE), Finland (FI), Latvia
216 (LV), Lithuania (LT), Norway (NO), and Sweden (SE); the Southern region by Italy (IT), Portugal (PT),
217 Spain (ES) and Turkey (TR); the Central region by Austria (AT), Czech Republic (CZ), Germany (DE),
218 Hungary (HU), Poland (PL), Slovakia (SK), Slovenia (SI), and Switzerland (CH); and the Western region
219 by Belgium-Flanders (BE-VLG), Belgium-Wallonia (BE-WAL), France (FR), Ireland (IE), the Netherlands
220 (NL), and the United Kingdom (UK).

221 2.1 Perspectives on knowledge availability and use – broad group of stakeholders

222 The broad group of stakeholders in the assessment consisted of farmers, advisors, representatives of
223 agricultural associations, NGOs, policy makers and the agricultural industry, which were members of
224 EJP SOIL national hubs or were linked to these. Interviews with stakeholders were conducted by the
225 national EJP SOIL members in their local language allowing for the best possible quality of
226 information. Participation in the EJP SOIL National Hubs was voluntary and open, but an initial
227 national identification of key players was conducted, which served as a basis for active recruitment.
228 In total, 791 stakeholders from 23 countries were interviewed for the national reports (Table 1).
229 Interviews were completed primarily as an online survey, but also face-to-face, by phone or video
230 call, or as part of a focus group. Also, the composition of stakeholders varied across countries due to
231 differences in organizational landscape and stakeholder availability. This variation in the number of
232 informants and their related stakeholder categories is a minor shortcoming of the analysis as the

233 perspective and methods of stakeholder consultation varied slightly across countries. Farmers are an
234 important stakeholder category for the objectives of this paper and these were not a part of
235 discussions across all countries since the National Hubs mostly engage stakeholders at an
236 organizational level. However, the practice perspective is also reflected by advisors and
237 representatives from farmers associations and industry. To reduce potential bias, national inputs
238 were consolidated and reported in a structured format with predefined questions by national EJP
239 SOIL partners who were familiar with the local conditions and discussions. Questions were based on
240 experiences from a series of European soil research projects, including RECARE, SoilCare, CIRCASA,
241 LANDMARK, PRO AKIS and AgriLink, addressing five predefined themes: 1) structure of the
242 agricultural soils knowledge system, 2) coordination of knowledge production and use, 3) ability of
243 the knowledge system to influence farming practices, 4) knowledge status relative to environmental
244 zones and 5) knowledge gaps (see Thorsøe (2021) for further methodological details).

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

253 2.2 Perspectives on knowledge availability and use - researchers

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

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

269 2.3 Synthesis

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

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

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

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

299 3. Results

300 3.1 Gaps in knowledge about sustainable soil management

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

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

318 were perceived to be among the challenges with most critical knowledge gaps. In Western Europe,
319 the most critical knowledge gaps were associated with the challenges of enhancing soil biodiversity,
320 ensuring optimal soil structure and enhancing water storage capacity.

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

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

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

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

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

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

362 management strategies, and the need for studies on land degradation processes and prevention
363 measures in a changing climate.

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

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

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

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

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

396 **3.2 Addressing knowledge gaps about sustainable soil management**

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

405 ***Gaps in knowledge transfer***

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

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

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

426 **1) Raising awareness**

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

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

451 improve dissemination, including training programmes for farmers and advisors, that have a direct
452 relationship with farmers is emphasized to be important.

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

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

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

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

478 **5) Targeting advice and information**

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

485 **6) Improving knowledge access**

486 Knowledge on sustainable soil management was often found to be fragmented across different
487 researcher groups, institutions, or even across countries, thus creating the need to compile
488 knowledge and make it more approachable. Although likely diverging across countries, interviews
489 with the broad group of stakeholders emphasized that digital communication, which has a broad
490 reach, is important to improve the availability of knowledge, including datasets, research results and
491 successful management strategies. It was suggested that accessible and comprehensive web-based
492 platforms for gathering and disseminating comprehensive national datasets if these already exist (as
493 well improving the resolution of the European datasets base) for instance integrating with social

494 media to facilitate online networking and community building. Soil maps were found to be difficult
495 to understand for outsiders, therefore, highlighting implications for practitioners were indicated as
496 an aspect in need of improvement. It is emphasized that this could be ensured, e.g. by developing
497 decision support tools that provide comprehensive advice on farmers' field practice, on nutrient
498 application, manure management, pest management, field traffic or other important issues. Locally
499 some decision support tools have been developed, such as Terranimo® (<https://www.terranimodk/>)
500 for assessing the effects of field traffic, but translation and a joint decision support platform is
501 requested.

502 **7) Providing incentives**

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

516 4. Discussion

517 4.1 Soil knowledge use and gaps

518 Across Europe, we found considerable variation in soil knowledge use and gaps with varying
519 importance for sustainable soil management. These findings reflect the diverse pedoclimatic
520 conditions and farming systems across Europe, as also emphasized in other studies (Frelid-Larsen,
521 2017; Hessel et al., 2022; Strauss, Paul, Dönmez, Löbmann, & Helming, 2023; Vanino et al., 2023).
522 Lacking knowledge use may either be the result of unavailability or insufficient transfer. Our study
523 finds both deficiencies, but the situation across the surveyed countries varied considerably.

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

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

535 Although diverging in composition and perspectives, the two groups both identified a number of
536 gaps in current knowledge availability and use, particularly with respect to SOC. Thus, we argue that

537 the main knowledge gaps are related to relevant soil threats (particularly loss of SOC, peatland
538 degradation, soil compaction), developing more models and monitoring programmes, and
539 effectively disseminating knowledge. This reflects that mitigating climate change and preventing soil
540 degradation using sustainable soil management practices has become an important concern across
541 Europe in policy as well as among practitioners. Further, across regions, the group of researchers
542 expressed an urgent need for research on deep carbon in the subsoil and its dynamics and
543 susceptibility to climate change.

544 However, given the composition of EJP SOIL, a number of countries in South and Southeast Europe
545 are not included in this assessment, including, Spain (not represented in the broad group of
546 stakeholders), Romania, Greece and the Balkans. Thus, in the ongoing Soil Mission research it is
547 important to ensure that the soil challenges that are prevalent in these countries are also
548 considered. A series of recent assessments of the soil health status and soil challenges in the region
549 indicate that challenges for these countries are comparable to other Mediterranean countries. E.g.
550 erosion and desertification are challenges across all countries (Petrescu-Mag, Petrescu, & Azadi,
551 2020; Ristić et al., 2020; Schismenos, Emmanouloudis, Stevens, Katopodes, & Melesse, 2022), whilst
552 contamination and soil sealing are also highlighted as additional issues across the Balkans (Ristić et
553 al., 2020). Further, as previously noted, although farmers are an important stakeholder category
554 they were not part of discussions across all countries. Therefore, additional knowledge gaps may
555 have featured more prominently if the composition of the stakeholders were different, including
556 gaps relating to the productive potential of farmland, such as irrigation, liming and, nutrient
557 management.

558 4.2 General implications for bridging knowledge gaps

559 To improve the AKIS and effectively address key soil challenges, such as the loss of SOC, poor
560 nutrient management, soil erosion, soil compaction and soil biodiversity loss, the coordination of a
561 broad suite of actors, including researchers, policy makers, practitioners and knowledge brokers is
562 required (DeCaro, Chaffin, Schlager, Garmestani, & Ruhl, 2017; Folke, Hahn, Olsson, & Norberg,
563 2005; Klerkx, 2020; Knierim et al., 2015). Further, measures with multiple beneficial effects on soils
564 often imply systemic changes in the farming system, as sustainable soil management is interlinked
565 with a number of farming operations (Strauss et al., 2023). However, as documented in this article,
566 the fragmented knowledge infrastructure and the lack of collaboration among different user groups
567 and scientific disciplines is of concern. If not overcome, this will hamper the ability of EU Member
568 States to meet the ambitious objectives of achieving land degradation neutrality, land-based climate
569 neutrality by 2035 and good soil health by 2050 as agreed in the EU soil strategy (ECA, 2021).
570 Ongoing degradation of soils, which contain large carbon stocks, including of agroforestry systems
571 and peatland ecosystems, where trees are cut or peatland drained (McDonald et al., 2021;
572 Tanneberger et al., 2021) indicates that soil use knowledge gaps are critical to fill as a basis for
573 meeting the wider strategic objectives of the European Commission.

574 In line with others, we contend that it is unlikely that increasing knowledge production and
575 knowledge transfer alone will not be sufficient to ensure a transition to sustainable soil management
576 (Dalkir, 2005; Ingram & Mills, 2019; Ingram et al., 2022; Rust et al., 2020; Thorsøe et al., 2019). It also
577 needs to be recognized that knowledge is embedded in a wider socio-material context that enables
578 or constrains the implementation of sustainable soil management, e.g. size and type of farm
579 machinery or mode of regulation (Huber-Stearns et al., 2017; Thorsøe et al., 2022; Visser et al.,
580 2019). Further, various socio-cultural aspects like trust, norms, connectedness and power influence
581 the capacity, ability and motivation of farmers to change their soil management practices (Rust et

582 al., 2020). This implies that a wide range of enabling conditions must be provided to ensure a
583 transition to sustainable soil management. Therefore, ensuring that supporting policies,
584 technological development, sociocultural perceptions, economic and market incentives, are all
585 aligned with the creation of research infrastructures and with new knowledge production and
586 application is important (Brady et al., 2022; Markard, Geels, & Raven, 2020).

587 Assessments of knowledge transfer via advisory programmes under the CAP programmes have
588 revealed that few farmers are reached and advice is insufficiently targeted to groups with specific
589 knowledge needs (Labarthe & Beck, 2022). Particularly with respect to sustainable soil management,
590 multi-scale character and diverse audience for advice constitute a complex arena for changing
591 farming practices (Ingram & Mills, 2019). Further, other European wide surveys indicate that farmers
592 diversity and the plurality of European farm advisory services constitute a hindrance to adoption of
593 sustainable management practices (Madureira, Labarthe, Marques, & Santos, 2022). On top of that,
594 the profound differences in pedo-climatic conditions and institutional approaches to soil
595 management interventions across European countries call for a greater simplification and coherence
596 of policy actions to ensure that national initiatives are adapted to local conditions (Hessel et al.,
597 2022; Ingram & Mills, 2019).

598 4.3 Bridging knowledge gaps in the EU Mission A Soil Deal for Europe

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

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

619 Although the Soil Mission and the proposal for a Soil Health Law presents a window of opportunity
620 for a transition towards sustainable soil management, there is currently no comprehensive
621 coordination to address soil threats and soil-related issues in the EU (Heuser, 2022). Further, other
622 issues beyond climate change also need consideration to ensure the fulfilment of the wider
623 sustainability goals of society, including biodiversity, food security and various socio-economic issues
624 (FAO, 2015a; IPBES, 2018). Working towards greater coherency of the EU policy architecture will
625 help to improve sectoral coordination and the full domestic implementation of current EU policies.
626 Therefore, actions to protect soils should not constrain our abilities to address these other key

627 societal challenges, but rather we should strive for synergies by working towards integrated systemic
628 solutions (Alrøe & Noe, 2014).

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

637 5. Conclusion

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

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

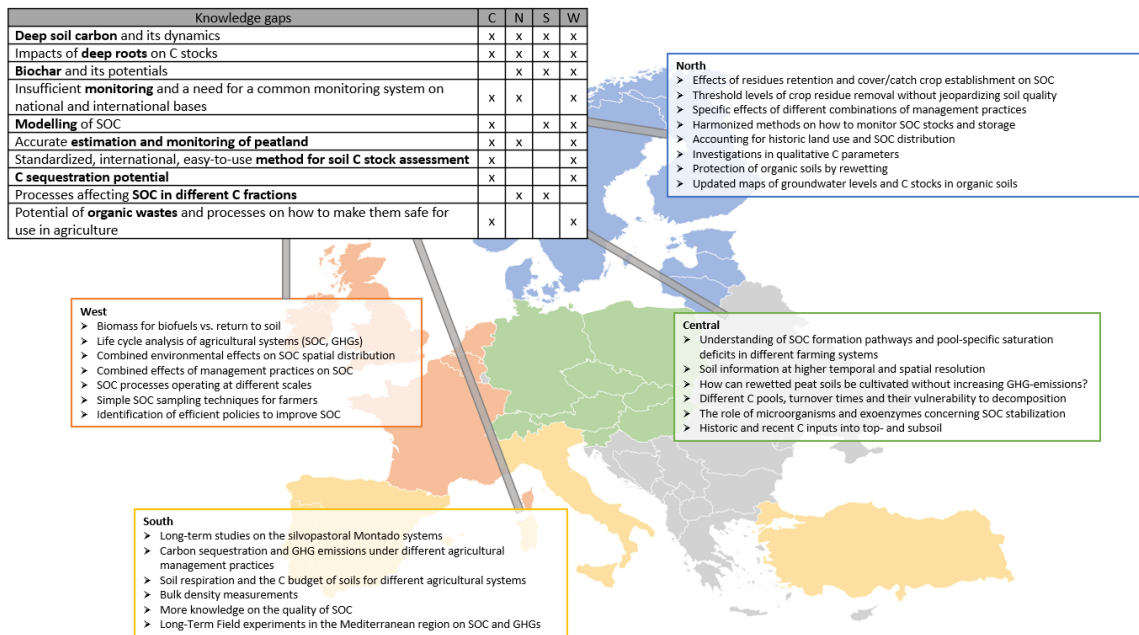
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658 **Table 1:** Composition of the broad group of stakeholders (Thorsøe, 2021).

		Policy-makers	Research communities	Research funders	Educational institutions and	Farmers & demonstration farms	Advisors	Farmers' organisations	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

661 **Table 2:** Number of researchers interviewed for the three specific topics within the EJP SOIL
662 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



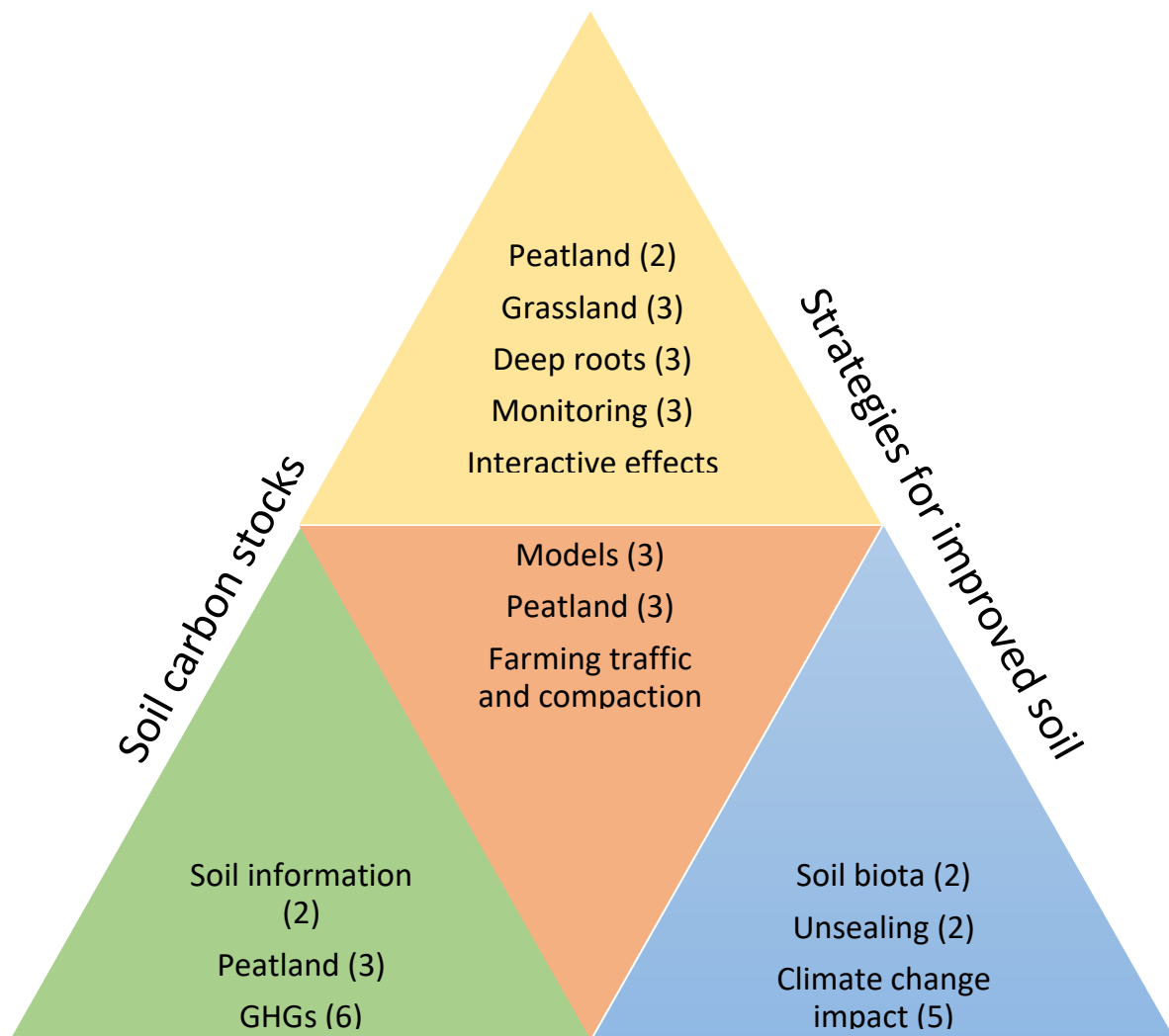
664

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

670

671

672



Soil degradation and

674 **Figure 2.** Overlapping knowledge gaps found in the three different topics (numbers in brackets
 675 indicate number of national reports mentioning overlapping knowledge gaps). The sides of the large
 676 triangle represent the three topics addressed by researchers, the corner triangles show overlapping
 677 knowledge gaps between two topics, and the inner triangle shows overlaps between all three topics
 678 (orange). Green: overlap between 'Soil carbon stocks' and 'Soil degradation and fertility'; blue:
 679 overlap between 'Soil degradation and fertility' and 'Strategies for improved soil management';
 680 yellow: overlap between 'Strategies for improved soil management' and 'Soil carbon stocks'. Source:
 681 Munkholm et al. (2021).

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

		Maintain/increase SOC	Avoid N ₂ O/CH ₄ emissions	Avoid peat degradation	Avoid soil erosion (e.g. water/wind/tillage)	Avoid soil sealing	Avoid salinization	Avoid contamination	Optimal soil structure	Enhance soil biodiversity	Enhance soil nutrient	Enhance water storage capacity
Central Europe	AT (Alpine South)	Yellow	Yellow	Grey	Yellow	Yellow	Grey	Grey	Red	Red	Red	Red
	AT (Continental)	Yellow	Yellow	Grey	Yellow	Yellow	Grey	Grey	Yellow	Yellow	Yellow	Yellow
	CZ (Alpine South)	Yellow	Yellow	Grey	Red	Yellow	Grey	Grey	Yellow	Yellow	Yellow	Red
	CZ (Continental)	Yellow	Yellow	Grey	Red	Yellow	Grey	Grey	Yellow	Yellow	Yellow	Red
	DE (Atlantic North)	Red	Yellow	Grey	Yellow	Yellow	Grey	Grey	Yellow	Red	Yellow	Yellow
	HU (Pannonian-Pontic)	Red	Yellow	Yellow	Yellow	Yellow	Grey	Yellow	Yellow	Yellow	Red	Red
	PL (Continental)	Yellow	Yellow	Grey	Yellow	Yellow	Grey	Grey	Yellow	Yellow	Yellow	Yellow
	SK (Continental)	Red	Yellow	Grey	Red	Yellow	Grey	Yellow	Red	Yellow	Red	Red
	SI (Alpine South)	Red	Yellow	Grey	Red	Yellow	Grey	Yellow	Yellow	Red	Red	Red
	CH (Continental)	Red	Yellow	Grey	Yellow	Yellow	Grey	Yellow	Yellow	Yellow	Yellow	Yellow
Northern Europe	DK (Atlantic North)	Red	Red	Red	Yellow	Yellow	Grey	Grey	Yellow	Yellow	Yellow	Yellow
	FI (Boreal)	Red	Yellow	Yellow	Yellow	Yellow	Grey	Grey	Yellow	Yellow	Yellow	Yellow
	LV (Nemoral)	Red	Red	Grey	Yellow	Yellow	Grey	Grey	Yellow	Yellow	Yellow	Yellow
	LT (Nemoral)	Red	Yellow	Grey	Yellow	Yellow	Grey	Grey	Red	Yellow	Red	Red
	NO (Boreal)	Red	Yellow	Grey	Yellow	Yellow	Grey	Grey	Yellow	Yellow	Yellow	Red
	SE (Nemoral)	Yellow	Yellow	Grey	Yellow	Yellow	Grey	Grey	Yellow	Yellow	Yellow	Yellow
Southern Europe	IT (Mediterranean North)	Red	Yellow	Grey	Red	Red	Red	Red	Yellow	Yellow	Yellow	Yellow
	IT (Mediterranean Mountains)	Yellow	Yellow	Grey	Yellow	Yellow	Grey	Red	Yellow	Yellow	Yellow	Yellow
	PT (Lusitanian)	Red	Yellow	Grey	Red	Yellow	Red	Red	Red	Red	Yellow	Yellow
	PT (Mediterranean South)	Red	Yellow	Grey	Yellow	Yellow	Grey	Grey	Red	Red	Yellow	Red
	TU (Anatolian)	Red	Yellow	Grey	Red	Yellow	Grey	Yellow	Yellow	Red	Yellow	Red
Western Europe	BE (F) (Atlantic Central)	Red	Yellow	Grey	Yellow	Yellow	Grey	Grey	Yellow	Yellow	Yellow	Red
	BE (W) (Atlantic Central)	Red	Yellow	Grey	Yellow	Yellow	Grey	Grey	Yellow	Red	Yellow	Yellow
	FR (Atlantic Central)	Red	Yellow	Grey	Yellow	Yellow	Grey	Yellow	Yellow	Yellow	Yellow	Yellow
	FR (Lusitanian)	Yellow	Yellow	Grey	Yellow	Yellow	Grey	Grey	Yellow	Yellow	Yellow	Yellow
	IE (Atlantic Central)	Red	Red	Red	Yellow	Yellow	Grey	Grey	Red	Red	Red	Red
	NL (Atlantic Central)	Red	Yellow	Yellow	Yellow	Yellow	Grey	Grey	Yellow	Yellow	Yellow	Yellow
	NL (Atlantic North)	Red	Yellow	Yellow	Yellow	Yellow	Grey	Grey	Yellow	Yellow	Yellow	Yellow
	UK (Atlantic North)	Yellow	Red	Yellow	Yellow	Yellow	Grey	Grey	Yellow	Red	Red	Yellow
	UK (Atlantic Central)	Red	Yellow	Yellow	Red	Red	Grey	Yellow	Red	Red	Red	Yellow

Legend	Very important soil challenge and very important research gap	Very important soil challenge and important research gap
	Important soil challenge and very important research gap	Important soil challenge and important research gap
	Other combinations	

690 **Table 4:** Replies to three questions regarding the strength of the knowledge system in the countries
 691 (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	Important	Important	Neutral
Belgium Flanders	Neutral	Less important	Neutral
Belgium Wallonia	Less important	Important	Neutral
Czechia	Less important	Important	Less important
Denmark	Less important	Less important	Less important
Finland	Neutral	Neutral	Neutral
France	Neutral	Neutral	Important
Germany	Very important	Less important	Less important
Hungary	Neutral	Less important	Less important
Ireland	Neutral	Less important	Neutral
Italy	Important	Important	Important
Latvia	Very important	Less important	Less important
Lithuania	Important	Less important	Less important
Norway	Neutral	Less important	Less important
Poland	Neutral	Neutral	Neutral
Portugal	Important	Important	Important
Slovakia	Neutral	Important	Important
Slovenia	Neutral	Less important	Important
Sweden	Neutral	Neutral	Neutral
Switzerland	Important	Important	Important
The Netherlands	Important	Less important	Less important
Turkey	Neutral	Neutral	Neutral
United Kingdom	Important	Less important	Less important



693 **Table 5:** Stakeholders' replies to the question: "How important are the following undertakings to
 694 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)							
	AT (Continental)							
	CZ (Alpine South)							
	CZ (Continental)							
	DE (Atlantic North)							
	HU (Pannonian-Pontic)							
	PL (Continental)							
	SK (Continental)							
	SI (Alpine South)							
	CH (Continental)							
Northern Europe	DK (Atlantic North)							
	FI (Boreal)							
	LV (Nemoral)							
	LT (Nemoral)							
	NO (Boreal)							
	SE (Nemoral)							
Southern Europe	IT (Mediterranean North)							
	IT (Mediterranean Mountains)							
	PT (Lusitanian)							
	PT (Mediterranean South)							
	TU (Anatolian)							
Western Europe	BE (F) (Atlantic Central)							
	BE (W) (Atlantic Central)							
	FR (Atlantic Central)							
	FR (Lusitanian)							
	IE (Atlantic Central)							
	NL (Atlantic Central)							
	NL (Atlantic North)							
	UK (Atlantic North)							
	UK (Atlantic Central)							

Legend	Very important	Important	Neutral	Less important	Not important at all
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696 Contributor Roles

697 Here please list your name and in parenthesis indicate your role in writing the paper according to the
698 [Contributor Roles Taxonomy \(CRediT\)](#) (Conceptualization; Data curation; Formal Analysis; Funding
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