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Research article

Barriers and opportunities of soil knowledge to address soil challenges: Stakeholders' perspectives across Europe☆

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ABSTRACT

Climate-smart sustainable management of agricultural soil is critical to improve soil health, enhance food and water security, contribute to climate change mitigation and adaptation, biodiversity preservation, and improve human health and wellbeing. The European Joint Programme for Soil (EJP SOIL) started in 2020 with the aim to significantly improve soil management knowledge and create a sustainable and integrated European soil research system. EJP SOIL involves more than 350 scientists across 24 Countries and has been addressing multiple aspects associated with soil management across different European agroecosystems. This study summarizes the key findings of stakeholder consultations conducted at the national level across 20 countries with the aim to identify important barriers and challenges currently affecting soil knowledge but also assess opportunities to overcome these obstacles. Our findings demonstrate that there is significant room for improvement in terms of knowledge production, dissemination and adoption. Among the most important barriers identified by consulted stakeholders are technical, political, social and economic obstacles, which strongly limit the development and full exploitation of the outcomes of soil research. The main soil challenge across consulted member states remains to improve soil

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organic matter and peat soil conservation while soil water storage capacity is a key challenge in Southern Europe. Findings from this study clearly suggest that going forward climate-smart sustainable soil management will benefit from (1) increases in research funding, (2) the maintenance and valorisation of long-term (field) experiments, (3) the creation of knowledge sharing networks and interlinked national and European infrastructures, and (4) the development of regionally-tailored soil management strategies. All the above-mentioned interventions can contribute to the creation of healthy, resilient and sustainable soil ecosystems across Europe.

1. Introduction

Life on Earth depends on healthy soils (EU, 2021), which provide humankind with a broad range of essential services, including provisioning (e.g., food and fuel), regulating (e.g., flood mitigation and water purification), supporting (e.g., soil formation and nutrient cycling) and cultural (e.g., recreation, aesthetic value) services (Millennium Ecosystems Assessment, 2003).

Soil health is an integrative property that reflects the capacity of soil to respond to agricultural intervention so that it continues to support both agricultural production and the provision of key ecosystem services (Kibblewhite et al., 2008). There is increasing agreement on the need to protect and enhance the quality of soil resources to better support ecosystem services and improve resilience in the face of climate change (Keesstra et al., 2016). Sustainable Soil Management, together with the restoration of degraded soils and the improvement of soil productivity have been identified as key action areas towards the achievement of important Sustainable Development Goals (SDGs). Key goals include SDGs 1 and 2 (nourishing and high-quality food accessible to all), SDG3 (reduced use of inputs potentially hazardous to health), SDGs 6 and 14 (water quality), SDG13 (climate mitigation) and SDG15 (sustainable use of terrestrial ecosystems), and indirectly contribute to achieve other SDGs (Kopittke et al., 2021; Visser et al., 2019; Bouma and Montanarella, 2016). In this context, advancing soil science research can greatly contribute to bridge the gap between soil science and societal needs, but this process requires a joint effort that involves a wide range of stakeholders (Mol and Keesstra, 2012). Therefore, in agricultural soils the question has to move from 'how farmers learn a new technique most efficiently', to 'how farmers, scientists and advisors can collaborate, re-negotiate existing and co-create new meanings for soil erosion and soil conservation' (Schneider et al., 2009).

The European Commission (EC) estimated that 60–70% of soils in the EU are unhealthy as a direct result of current management practices (Veerman et al., 2020). Major soil threats identified by the EC include soil erosion by water and wind, declines in soil organic matter (SOM) in peat and mineral soils, soil compaction, sealing, contamination, salinization, desertification, and declines in soil biodiversity (EC, 2006; Kibblewhite, 2012). Each threat represents also a challenge to be overcome for preserving soil from degradation. The new EU soil strategy for 2030 sets out a framework and concrete measures to protect and restore soils and overcome soil challenges as a contribution towards a modern, low-carbon, resource-efficient and competitive economy (EU, 2019). The European Union has launched the European Joint Programme for Soil "Towards climate-smart sustainable management of agricultural soils" (EJP SOIL, 2020–2025) with the aim of building an integrated European research community on agricultural soils, and enabling an environment that maximizes the contribution of agricultural soil to key societal challenges such as food and water security, climate change adaptation and mitigation, biodiversity preservation and human health. Beyond performing dedicated research activities to i) create new soil knowledge, EJP SOIL aims to optimize all the phases of soil knowledge management, such as ii) knowledge harmonization, organization & storage; iii) knowledge sharing & transfer; and iv) knowledge application (Dalkir, 2005). EJP SOIL aims to achieve its overarching goals through a participatory approach, based on the interaction among scientists, coming from several European countries and with various interests and competencies on soil related themes, and multiple stakeholders both at national and regional levels.

This paper summarizes the outcomes of a stakeholder consultation campaign carried out in 20 countries within the EJP SOIL consortium (Fig. 1), to identify and prioritize the main barriers and opportunities for soil knowledge at the European level. The survey was organized in a way to firstly prioritize key soil challenges of each country participating in the consultation campaign. Moreover, the main barriers and opportunities currently characterizing soil knowledge in each country were identified. Ultimately, the perception of stakeholders on how to optimize the management of soil knowledge in a view to leverage strengths and opportunities, thus contributing to overcoming barriers and addressing identified challenges, was investigated.

2. Material and methods

2.1. Methodological framework

Participatory multi-stakeholder consultations were conducted in 2020, in 20 European countries participating in EJP SOIL (Fig. 1) to gather the perceptions of stakeholders (e.g., farmers, NGOs, agro-industries, public administrations, agricultural organizations, agricultural schools, and scientific researchers) on barriers about soil knowledge and actions to address soil challenges. Data were collected through individual on-line surveys, virtual interviews, and web-meetings.

Data collection at national level required firstly the development of a common methodological framework. This included guidelines (see Supplementary material) and basic templates for implementing the consultation and prepare reports on results, to be used in the various EJP SOIL participating countries. Building on this framework, each national

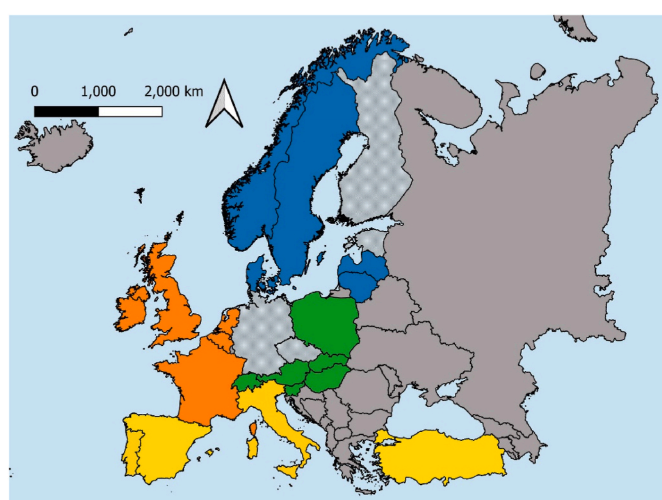

Fig. 1. EJP SOIL Countries participating in the consultation and their distribution in European geographical zones (green: Central Europe, orange: Western Europe, blue: Northern Europe, yellow: Southern Europe). Countries highlighted in light grey are members of the EJP Soil consortium but did not participate in the consultation. Countries marked in grey are not participating in the EJP Soil. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

team was responsible to: (i) design tailored national questionnaires using national language; (ii) carry out the interviews of national stakeholders; and (iii) collate collected data in the reporting template. National reports from all countries participating in the consultation campaign were collected, elaborated and analysed. The results of the consultation campaign conducted at European level are reported in this paper.

The guidelines included a background section and three inquiring sections (A – C). The background section was dedicated to explaining the criteria adopted for the selection of targeted stakeholders and briefly explaining the scope of the work. The first section (A) was aimed at collecting general information about each specific country as well as stakeholder personal information, such as gender, age, education, occupation. In the second section (B), stakeholders were asked to prioritize the most relevant soil challenges identified by the EJP SOIL consortium (i.e. improving/conserving soil organic matter and peat soil, water storage capacity, nutrient retention and use efficiency, soil biodiversity and disease suppression, avoiding GHG emissions, soil erosion, salinization, and acidification, soil sealing and compaction, and soil contamination) according to their relevance for the specific stakeholder country. In the last section (C), stakeholders were asked to identify country's barriers and opportunities to address the most relevant soil challenges. To this end, stakeholders were invited to provide a multiple selection choice of already defined barriers and opportunities and to further add other specific barriers and opportunities related to their country's context. A schematic view of the above-described workflow is reported in Fig. 1 in Supplementary material.

Data gathered and reported by each national team in the common template were then harmonized and analysed by aggregating the results per country.

2.2. Data analysis

Identified barriers and opportunities were classified and grouped into major "categories" representing scientific disciplines or fields of action (e.g., technical, political, social). Visualization analysis of the occurrence of barriers and actions for each phase of soil knowledge management was performed running a correspondence analysis using XLSTAT (Addinsoft, 2016), in order to identify any relationships between soil knowledge and barriers and opportunities identified by the consulted stakeholders.

3. Results

3.1. Stakeholder analysis

The consultation campaign involved a total of 314 stakeholders (hereafter CSs), of which 27% were from Central Europe, 26% from Northern Europe, 22% from Western Europe and 21% from Southern Europe (Table 1). There is no gender equality since 60.8% of CSs are male, 34.5% female and the rest did not respond to that question. 32.8% of CSs were between 41 and 54 years old, 25.7% were between 55 and 64 years old, 23.6% were under 40 and 5.4% over 65 years old, the rest 12.5% did not provide information on their age. The most represented stakeholder categories were: researchers (29%), farmers and farmer associations (25%), and public administrators (15%). Other categories, such as employees in educational institutions (2%), NGOs (1%) and agroindustry (1%) were less represented. 14% of CSs did not belong to any of the pre-identified stakeholder categories.

Stakeholders were asked to prioritize pre-identified soil challenges for their own country, ranking them from 1 (low priority) to 10 (high priority). Therefore, it was further possible to evaluate the weighted importance of each soil challenge among member states. The results of the assessment were obtained by combining all information and weighting the position from 1 to 10 in order of importance given by the stakeholders. A weight of 10 was assigned to position 1, a weight of 9 to position 2, etc. The results confirm that "improving soil organic matter and peat soil conservation" was the priority (16.7%), followed by "nutrient retention" (14.2%) and "improving water storage capacity" (13.3%). The weighted calculation highlights also that, "erosion", "soil compaction", and "soil biodiversity" were very important according to stakeholders perception, with 11.8%, 10.8% and 10.6% respectively. "GHG emissions" and "Soil sealing" have significant importance as they were identified as first priority respectively by 9.2% and 7.1% of consulted stakeholders.

The aggregation of results for the four main geographical zones of Europe (Table 2) shows that "improving soil organic matter & peat soil conservation" was recognized as the priority soil challenge for all zones except for Southern Europe, for which "improving water storage capacity" was selected as the priority soil challenge.

With regards to soil knowledge management, stakeholders identified 102 barriers and 107 opportunities as suitable to overcome them (Tables 1 and 2 in Supplementary material). Stakeholders from Southern

Table 2
Soil challenge defined as the top priority by stakeholder in the various European Geographic Zones. (SOM = soil organic matter, GHG = greenhouse gases, I = improving, A = avoiding).

	Northern Europe	Western Europe	Central Europe	Southern Europe
SOM & peat soil conservation (I)	42%	40%	31%	16%
Water storage capacity (I)	14%	8%	13%	39%
Soil sealing (A)	6%	3%	17%	18%
Nutrient retention or use efficiency (I)	17%	6%	5%	12%
Erosion (water/wind/tillage) (A)	6%	7%	12%	10%
Soil compaction (A)	7%	7%	12%	0%
Soil biodiversity (I)	3%	11%	5%	2%
GHG emissions (A)	1%	16%	1%	2%
Contamination (A)	6%	0%	0%	0%
Disease suppression (I)	0%	0%	3%	0%
Salinization and acidification (A)	0%	2%	0%	0%

Table 1
Number of stakeholders participating in the consultation, per country and geographical zone.

Country	Geographical Zone	No. of stakeholders	Country	Geographical Zone	No. of stakeholders
Austria	Central Europe	9	**Poland**	Central Europe	10
Belgium	Western Europe	26	**Portugal**	Southern Europe	25
Denmark	Northern Europe	11	**Slovakia**	Central Europe	9
France	Western Europe	5	**Slovenia**	Central Europe	26
Hungary	Central Europe	15	**Spain**	Southern Europe	20
Ireland	Western Europe	5	**Sweden**	Northern Europe	3
Italy	Southern Europe	20	**Switzerland**	Central Europe	16
Latvia	Northern Europe	56	**The Netherlands**	Western Europe	12
Lithuania	Northern Europe	10	**Turkey**	Southern Europe	4
Norway	Northern Europe	7	**United Kingdom**	Western Europe	25

Europe listed the highest number of barriers (Fig. 2(a)) followed by CSs of Central and Northern Europe. Stakeholders from Central Europe identified the highest number of opportunities (Fig. 2(b) and Table 3), followed by Northern and Western Europe CSs.

3.2. Barriers affecting soil knowledge management

In almost all geographic zones, CSs identified numerous and highly diversified types of barriers (Table 1 in Supplementary material) which have been grouped into 7 main categories (Table 4). 28% of identified barriers are related to “Capacity building”, 18% to “Technical”, 17% to “Networks”, 13% to “Communication”, 11% to “Economic” and “Political” and only 2% to “Social” category.

4Concerning the development of soil knowledge, the major barriers identified by CSs are related to the categories “Capacity building” (52%), “Networks” (19%) and “Economic” (11%) (Table 4). For soil knowledge application, barriers are distributed over all the categories identified, especially “Political”, “Capacity building” and “Economic”. For soil knowledge harmonization, organization, and storage, 57% of barriers belong to the “Technical” category and 24% to “Capacity building”. For soil knowledge development, 52% of barriers are related to “Capacity building”, and 19% to “Network”. “Social” barriers have been identified only in relation to the soil knowledge application.

The first and the second principal components of the correspondence analysis explained 78.8% (54% and 24.8%, respectively) of total inertia (Fig. 3). Axis 1 was positively correlated with “Technical” barriers and negatively correlated with “Communication” and “Networking” barriers. Axis 2 was positively correlated with “Communication” and negatively with “Economic” barriers. According to the results of the correspondence analysis, the “Technical” barriers are associated to the following phases of the soil knowledge: harmonization, organization, and knowledge storage, while the “Communication” constraints are associated with soil knowledge sharing. The other barriers appeared to be more closely related to the development (e.g., economic and capacity building) and application of soil knowledge (e.g. political), as shown in Fig. 4.

Twenty-seven disaggregated barriers for **soil knowledge development** were indicated by respondent countries (Table 3 in Supplementary material). The first four barriers were indicated by 41.2% of the respondent countries: ‘Lack of relations among research, advisory services and farmers’ and ‘Financial resources allocated to soil research are not sufficient’ were both indicated by 9.9% of the respondent countries, followed by both ‘Lack of public-private partnership on soil research’ (7.4%), and ‘Lack of training for advisors and farmers on soil-related issues’ (7.4%).

Twenty-seven barriers for **knowledge sharing and transfer** were indicated by respondent countries: the first five were identified by 55.9% of respondent countries (Table 4 in Supplementary material). In detail, ‘Networks science-science, science-farmers, science-advisors, science-society, science-policy are not established’ was identified by 16.1% of respondent countries followed by ‘Communication among researchers and farmers is not effective’ (14%), ‘Dissemination is missing, insufficient or does not convey useful information’ (9.7%), ‘Lack of training for farmers and advisors for soil-specific topics’ (8.6%), and ‘Communication is not clear for all stakeholder categories’ (7.5%).

For **knowledge harmonization, organization, and storage**, twenty-one barriers were indicated by CSs (Table 5 in supplementary material): the first five were indicated by 61.5% of CSs. In detail, ‘Different methodologies used for soil sampling, analysis and mapping or storage’ was indicated by 14.8% of the stakeholders, followed by ‘Outdated information’ (12.5%), ‘Data fragmentation’, ‘Lack of common data policy’, and ‘Dispersed storage of data, often not available to the public’, which together cover 34.2% of the responses because they were each indicated by 11.4% of respondent countries.

For **knowledge application**, the four most mentioned barriers were indicated by 42.3% of CSs (Table 6 in supplementary material). In detail, ‘Yields and profits may not respond as farmer expect’ was indicated by 14.4%, followed by ‘Lack of good policies and incentives’ (10.6%), ‘Technological constraints’ (9.6%) and ‘community pressures’ (7.7%).

3.3. Opportunities through (improved) soil knowledge management

As in the case of barriers, the type of opportunities proposed to deal with the identified constraints and to overcome soil challenges, are numerous and highly diversified (Table 2 in supplementary material). Opportunities vary from the development of good communication/dissemination strategies for soil knowledge to the creation/improvement of data storage with international standards. Opportunities identified by stakeholders have been grouped into 7 categories: “Capacity building” (35%), “Technical” (19%), “Economic” and “Communication” (almost 14% each), “Networks” (8%), “Political” (6%), and “Social” (4%.)

Concerning the development of soil knowledge, the main opportunities (Table 5) identified by CSs are related to “Capacity building” (55%), “Economic” (21%) and “Network” (17%) categories. For sharing and transferring soil knowledge, opportunities are distributed in all the

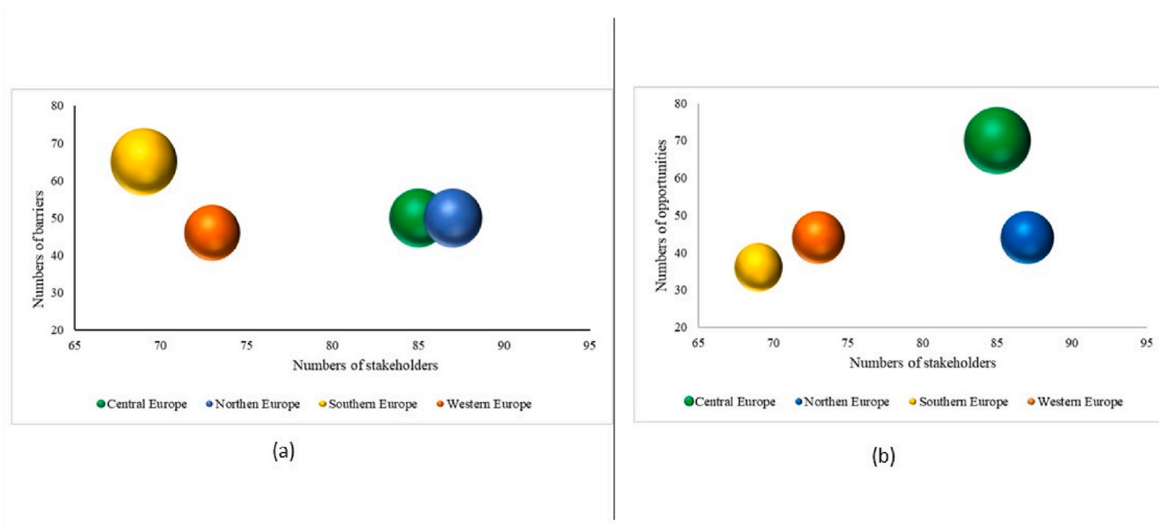

Fig. 2. Numbers of stakeholders and numbers of barriers (a) and opportunities (b) identified per each EU Geographic Zones. The size of the spheres represents the percentage of barriers and opportunities out of the total identified.

Table 3
Numbers of barriers and opportunities identified by stakeholders along the soil knowledge management process, per each European Geographic zones.

	Northern Europe	Western Europe	Central Europe	Southern Europe	Total
Soil Knowledge			**Barriers**		
Development	22	35	29	35	121
Sharing and transfer	16	30	23	24	93
Harmonization, organization and storage	12	29	20	27	88
Application	15	33	25	31	104
			Opportunities		
Development	20	34	35	24	113
Sharing and transfer	13	34	28	17	92
Harmonization, organization and storage	10	25	28	13	76
Application	21	30	27	19	97

Table 4
Percentage of barriers related to soil knowledge identified by stakeholders in the 20 countries involved in the consultation campaign. Individual barriers are summarized in categories.

	Soil Knowledge Management phase				
Category of barrier	***Development***	***Sharing and transfer***	***Harmonization, organization and storage***	***Application***	***Total***
Capacity building	52	19	24	18.5	28
Communication	4	33		11	13
Economic	11	7	5	18.5	11
Networks	19	26	9	11	17
Political	7	11	5	19	11
Social				7	2
Technical	7	4	57	15	18
Total	100	100	100	100	100

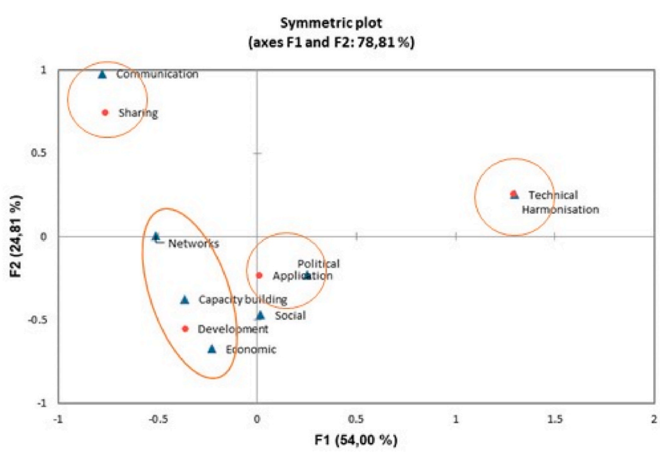

Fig. 3. Correspondence Analysis on identified barriers to sustainable agriculture for soil knowledge in the 20 countries involved in the consultation. Red dots represent soil knowledge management phases. Blue triangles stand for barrier categories. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

categories identified, especially in "Capacity building" and "Communication". For soil knowledge harmonization, organization, and storage, 59% of barriers were identified in the "Technical" and 24% in the "Capacity building" categories. For soil knowledge application, 26% of opportunities are related to the "Economic" category, 19% to "Capacity building" and "Communication" groups and 15% to "Political and "Technical" ones. "Social" barriers have been indicated as affecting knowledge sharing and transfer, as well as knowledge application.

The first and the second principal components of the correspondence analysis explained 86% of total inertia, respectively 57.7% and 28.3% (Fig. 4). Axis 1 was positively correlated with "Technical" and negatively with "Networking" opportunities; axis 2 was positively correlated with "Communication" and negatively with "Economic" opportunities. According to the results of the correspondence analysis, the "Technical" opportunities are strictly related to soil knowledge harmonization, organization, and storage, while the "Communication", "Networks" and "Social" actions to overcome constraints are more related to sharing and transfer of soil knowledge. "Political" opportunities are related to soil knowledge application, while "Capacity building" and "Economic" opportunities are more linked to soil knowledge development to overcome soil challenges.

The first four **opportunities for knowledge development** (Table 7 in supplementary material), were indicated by the majority (47.9%) of respondent countries. In detail, 'Increasing funding for soil related research' was indicated by 14.2% of respondent countries, followed by 'Supporting multi- and trans-disciplinary research' that was identified by 13.3% of respondent countries. The 'Activate/valorise/fund long term experiments' opportunity was indicated by 12.4% of respondent countries, while 'Increasing the number and improving curricula of the soil science students' was indicated by 8.0% of respondent countries.

More than thirteen **opportunities for knowledge sharing and transfer** were identified by respondent countries (Table 8 in supplementary material). The first four opportunities for knowledge sharing and transfer were indicated by 46.1% of respondent countries. In detail, 'Establishment of permanent national networks science-science, science-farmers, science-advisors, science-society, science-policy' was indicated by 14.1% of respondent countries, followed by 'Improvement of targeted and effective dissemination' and 'Making dissemination mandatory in all funded projects' (10.9% each), and 'Better/effective communication to increase awareness on the importance of soil in society' (9.8%).

More than seven **opportunities for knowledge harmonization, organization and storage** were indicated by respondent countries (Table 9 in supplementary material). The first four were indicated by 76.3% of respondent countries. In detail, the first three opportunities (i.e., 'Creation of national infrastructures and interactive, web-based communication of soil data', 'Promotion of harmonized and standardized methodologies', and 'Validation and integration of large data sets by using new Information Communication Technology (ICT) tools') cover together 60.5% of respondent countries. They were followed by 'Data storage with international standards', which represents 15.8% of the responses.

Twenty-eight **opportunities for knowledge application** were indicated by respondent countries (Table 10 in supplementary material). The first three were indicated by 59.6% of respondent countries. In detail, the first opportunity (i.e. 'Development of region-specific soil

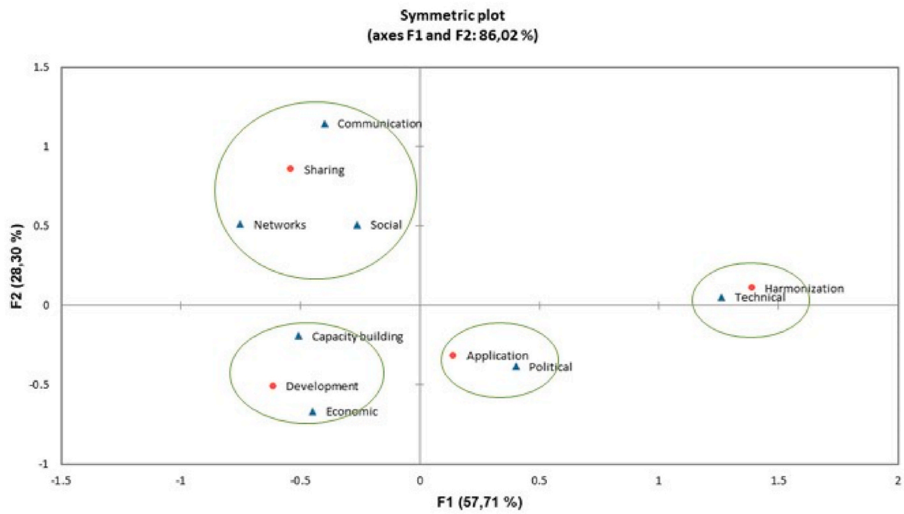

Fig. 4. Correspondence Analysis on identified opportunities to overcome soil challenges through soil knowledge in the 20 European countries involved in the campaign. Red dots represent soil knowledge management phases. Blue triangles stand for opportunity categories. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 5
Percentage of opportunities related to soil knowledge identified by stakeholders in the 20 countries involved in the consultation campaign. Individual opportunities are summarized in categories.

	Soil Knowledge (%)				
Category of opportunities	***Development***	***Sharing and transfer***	***Harmonization, organization, and storage***	***Application***	***Total***
Capacity building	55	37	23	18.5	35
Communication		26	6	18.5	14
Economic	21	6		26	14
Networks	17	11			8
Political		3	12	15	6
Social		6		7	4
Technical	7	11	59	15	19
Total	100	100	100	100	100

management strategies') represents 17.5% of the responses, followed by 'Good policies and incentives with effective policy measures' (14.4%), and 'Farmers have adequate ICT tools and use them' (11.3%). At the same time, 'Existence of specific mechanisms to support farmers in applying soil knowledge', and 'Soils are better integrated in the circular economy and bioeconomy' together cover 16.4% of the responses, having been each indicated by 8.2% of respondent countries.

4. Discussion

Soil health remains crucial for delivering food security and ecosystem services (Key et al., 2016) and could be enhanced by increases in soil organic matter content, by conserving or restoring degraded (drained) peat soils, by enhancing nutrient contents and retention capacity as well as water storage capacity and regulation. This study is a result of a multi-stakeholders consultation conducted in 20 countries across Europe through a standardized methodology which allows for the comparability and aggregation of collected data. Findings from this study, beyond identifying the most relevant soil challenges at European level, demonstrate how these priorities vary across the four geographic zones of Europe. For example, "improving SOM & peat soil conservation" was the priority soil challenge for most zones except for Southern Europe, where "improving water storage capacity" has been recognized as the priority soil challenge. These two soil challenges are strictly interconnected: SOM contributes to soil structure and, hence, to improve water infiltration and water holding capacity of soil and, at the same time, it is affected by water resource availability, which is hampered by climate change especially in Mediterranean areas (Fader et al., 2020; Saadi et al., 2014; Mereu et al., 2021; Francaviglia and Di Bene, 2019). The key role of SOM in agricultural soils in terms of climate change mitigation is well recognized by the EU, as highlighted in the scientific literature (Navarro-Pedreño et al., 2021; Farina et al., 2017) and supported in various EU strategies developed under the European Green Deal, such as the "Farm to Fork" and the "European Soil Strategy" (Montanarella and Panagos, 2021), and by the 4p1000 initiative (Rumpel et al., 2020). Nevertheless, recent EJP Soil analysis of data collected through national stakeholders consultations across EU Member States, highlighted the inadequacy of national ongoing policy-making for soils due to an insufficient focus on elements that are important according to current soil research, e.g., perspectives regarding the loss of SOM, exploring the effects of climate change and mitigation, and preventive measures (Keesstra et al., 2021; Jacob et al., 2021). A range of targeted policies and measures are required at national level to tackle the above mentioned soil related issues and shall be developed in consultation with local and regional governmental organizations. Stakeholders required also clear policy to encourage farmers to sustainably manage their soils. To this scope, financial support is an important instrument.

Furthermore, this study has identified through a participatory approach, a wide range of barriers and opportunities linked to, and dependent on, soil knowledge, by specifically attributing them to the various phases of the soil knowledge management process. Results from Correspondence Analysis show that soil knowledge development is hampered by capacity building and economic barriers, which could be overcome by creating new specific opportunities within the same category (Figs. 3 and 4), as increasing funding for soil research. In this context, EJP SOIL represents a starting point to translate all the identified opportunities for multi- and trans-disciplinary research activities into practice, thanks to the availability of dedicated financial resources. In fact, EJP soil contributes to maintaining and valorising long-term field experiments; promoting soil education and fostering the creation of soil knowledge networks and national infrastructures liaising among them at European level.

Soil information harmonization, organization and storage at national and European level are hampered by the lack of pan-European standardized methods for soil sampling, analysis and mapping, and the availability of outdated soil information, which have been recognized as technical barriers to soil knowledge (Fig. 3). Lack of harmonization across Europe causes data fragmentation and prevents the development of high-quality soil datasets, which are key to support decision-making processes. These barriers are also largely recognized by the international scientific community who has recently undertaken multiple initiatives aiming at harmonising soil analytical methods and data, such as the Global Soil Partnership (GSP) and under its auspices the Global Soil Laboratory Network (GLOSOLAN), launched respectively in 2011 and in 2017, and the EU Soil Observatory (EUSO). There is increasing evidence that the creation of standardized data protocols, the promotion of interoperability of data and access to data and software, are vital to share, discover, combine data from similar or different sources (Janssen et al., 2017; Bispo et al., 2017; Bouchez et al., 2016), as also highlighted in this study. Available, digitalized, standardized soil data constitute a precious knowledge base for decision-making to develop effective policies and strategies for soil management guaranteeing the delivery of multiple ecosystem services, as demonstrated for example in studies from France (Bardy et al., 2018) and Scotland (Prager and McKee, 2014). New technologies (mobile tools, remote and proximal sensing) are sufficiently developed to be used in the agricultural sector by farmers, citizens and organizations. Nevertheless, this requires the overcoming of existing ICT gaps.

Soil knowledge sharing and transfer between science and the wider society are affected by multiple constraints and, in particular, by communication related obstacles (Fig. 3). Soil knowledge, in fact, is not always effectively conveyed to farmers, while dissemination remains insufficient or results poorly clear for many stakeholder categories (Table 4 in supplementary material). Fostering dialogue between scientists and key stakeholders at European, national and local levels, has been identified as a key priority to overcome the most important barriers to soil knowledge sharing such as the ones related to network, communication and traditional soil management practices (Fig. 4). This priority is among the targets of EJP SOIL, which aims to strengthen a science-policy interface in the area of agricultural soil management, establishing open dialogue and active engagement with policy makers. Nevertheless, EJP SOIL leaves still unbridged the gap between scientists and end-users, whose importance, highlighted by this study, is in accordance with previous results from Key et al. (2016). The last underlined the importance of a two-way knowledge exchange, in particular between researchers and practitioners to effectively improve soil health. Therefore, the implementation of additional bottom-up activities, such as round tables, training of trainers and farmers field school shall be encouraged by future EU actions to ensure a permanent and effective exchange of knowledge between science, end-users and policy makers.

The above-mentioned lack of communication affecting soil knowledge sharing is, probably, among the factors that cause the lack of evidence-based policies and incentives useful to support farmers and other end-users in the application of soil knowledge (Fig. 3). Other barriers affecting soil knowledge application include economical, technical, and political obstacles (Fig. 3 and Table 4). In particular, weak interlinkages, or the scarcely prompt translation of soil knowledge in innovative technical solutions as well as the slow development of policies and measures aiming at supporting their implementation, are significant impediments to the adoption and expansion of most soil management schemes. Therefore, to achieve global or regional impacts, substantive efforts shall be taken to strengthen an effective dialogue between science and policy realms, in a way to facilitate development and sharing of soil knowledge that foster, on its own, the development of a supporting legal framework that facilitate the adoption of soil knowledge (Amundson, 2020), such as its translation in innovative technical solutions and their implementation.

Our stakeholder consultation led to results similar to that of Demenois et al. (2020) regarding barriers and strategies to implement soil management that boost SOC sequestration. They found that most barriers were not technical, but rather related to access to knowledge, lack of training, management, costs or social pressure. As shown in Table 2 in supplementary material, the opportunities are mainly political: the “development of region-specific soil management strategies” and “good policies and incentives with effective policy measures” are recommended to support all actors in the agricultural systems, in particular farmers, in applying soil knowledge and new technologies and, to improve their income and wellbeing. These concepts have also been confirmed by Löbmann et al. (2022), where a group of experts underlined the need for more effective and coherent policies with a view on long-term effects, including sustainable soil management guidelines and the release of subsides linked to the actual adoption of good practice proved by monitoring of the soil status. The path towards innovative soil management and its maintenance for future generations require policies, programs, and cooperation at several levels in the science-societal framework. Despite the scientific and societal interest in soils, as of today there is no binding global treaty pertaining to soil management (Lago et al., 2019).

5. Conclusions

This study identified, through a participatory approach and a standardized methodology, the main soil challenges at the European level, and highlighted how these varies across the four geographic regions of Europe. The priority challenge in Southern Europe is the need to improve soil water storage capacity, while in the rest of Europe, the conservation of SOM and peat soils is the priority. These results, obtained from the consultation of a widely varied multi-stakeholder working group, match with the views of the science community. Nevertheless, although these challenges have been largely recognized and tackled by policy strategies recently released at European level in the framework of the EU Green Deal, they are still waiting for being translated in concrete directives, policies and measures, monitoring and evaluation systems to be adopted and transposed at national level.

Furthermore, the stakeholder consultations revealed a consensus on the fact that improving soil knowledge is key to address current and future soil challenges.

Although stakeholders come from different regions across Europe, they had similar views on the major barriers affecting soil knowledge management. Overall these barriers hinder three important needed actions: (i) the proper development of new knowledge; (ii) the effective sharing of soil knowledge; and (iii) the actual use and valorisation of the outcomes achieved through soil research by transferring key soil management knowledge to end-users. The outcomes of this work, implemented at European level, can guide the drawing of policies and measures fostering opportunities for improving soil knowledge towards addressing the main European soil challenges. This study suggests Europe to build on the outcomes of EJP SOIL e.g. by ensuring continuity to the European soil network and sharing knowledge platform, at the same time continuing to strengthen the dialogue between science and policy and introducing new action to address the weak bridges currently existing at the science-to-practice interface.

Credit author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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