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Scaling Decision-Support Tools to Promote Soil Health: Insights From Stakeholders in Europe and Turkey

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ABSTRACT

Soil health and climate change are increasingly impacting agriculture across Europe. Decision support tools (DSTs) have emerged as essential tools to help make accurate, evidence-based agricultural decisions aimed at enhancing productivity, profitability, and effective soil health management. Nevertheless, the adoption of these tools remains limited among farmers and varies across different regions. The aim of this study was to investigate, through a participatory approach, the challenges and drivers influencing the uptake and adoption of DSTs for sustainable soil management in Europe and Turkey. Our goal was to engage various stakeholders to identify the challenges and drivers associated with this process and collaboratively develop actionable recommendations to expand the application of DSTs. Multi-stakeholder workshops were conducted in Italy, Latvia, Sweden and Turkey, bringing together end-users, farmers, advisors, tool developers, researchers and policymakers from diverse agricultural contexts. The discussions during these workshops addressed the current use of DSTs, barriers to adoption, and potential solutions for scaling their use. The findings revealed that the primary barriers to adoption and scaling included costs, tool viability, data complexity, limited access to technical support, compatibility issues and insufficient marketing. To overcome these barriers and enhance the appeal of DSTs to users, stakeholders highlighted the necessity for user-friendly, affordable tools that offer enhanced transparency, real-time information, and adaptability to local farming conditions. Furthermore, stakeholders emphasised the importance of user-driven designs that could stimulate the innovation process and consider the interactions between human and technology. This study emphasises the complexity of adopting and scaling DSTs and the need for considering the local agricultural context. Stakeholder insights were categorised into a set of recommendations such as defining the scope of DSTs application, enhancing capacity building, creating a road map for stakeholders, and considering regional disparities in the participatory implementation process. A systematic, participatory approach is essential for addressing the different dimensions of the DST adoption and scaling process while taking into account regional differences in conditions and user needs.

Summary

- A systematic participatory approach to DST adoption is required to address the real needs of end-users in different agricultural contexts.
- Cross-sector collaboration is needed for the future development and implementation of DSTs.
- Tailored solutions and targeted funding are required to support the adoption of DSTs by different end-users across different regional contexts.
- Decision-support tools are essential for facilitating the transition to sustainable soil management practices in agriculture.

1 | Introduction

The growing global demand for food, driven by population growth, is significantly impacting the environment and agricultural productivity (Becker and Fanzo 2023; FAO 2017). Soil functions are essential to ecosystem services, directly contributing to the production of goods and services vital to human society and the environment (Debeljak et al. 2019). Various policies have been developed to support the sustainable development of agriculture and promote soil health. The European Green Deal and the Common Agricultural Policy (CAP) emphasise the importance of reducing agriculture's environmental footprint while ensuring food security and economic viability. Decision support tools (DSTs) play an essential role in solving the complex challenges facing modern agriculture to promote sustainability. These tools integrate diverse information, enabling farmers to analyse data and make informed decisions. As stakeholders and farmers encounter a vast variety of information and data from environmental conditions to economic and crop data—transforming this information into actionable decisions becomes a major challenge (Rose et al. 2016). In this context, DSTs are emerging as essential tools for facilitating accurate, evidence-based agricultural decisions. In a previous study, we performed a stocktake on the prevalence and use of DSTs within Europe. Despite the development of many DSTs, their adoption by farmers remains limited (Akaka et al. 2024; Warren Raffa et al. 2025).

Different studies have addressed the challenges and limiting factors associated with the implementation of DSTs. Factors related to both the characteristics of the farms and the characteristics of the farm owners have been found to significantly affect the adoption of new technologies in agriculture (Bucci et al. 2019). According to Nowak (2021), the factors influencing farmers' non-adoption of technologies can be classified into two main categories: factors that make farmers unable to adopt (such as economic constraints or lack of access to resources and knowledge) and those related to farmers' resistance to change (such as scepticism about new technology or uncertainty regarding its benefits). Additionally, Thar et al. (2021) identified that a key reason for the limited adoption of DSTs is that many of these tools fail to account for the complexities and heterogeneity of smallholder farming systems. Smallholder farmers often face unique challenges that differ significantly from those faced by large-scale farms, making one-size-fits-all solutions inadequate. Agricultural transition is not characterised by the rapid, linear adoption of emerging technologies and requires time to scale (Rose et al. 2023). Scaling DSTs involves both scaling out and scaling up to expand their use and reach among various farmers and across different regions for effective and greater impact (Seid et al. 2003; Zossou et al. 2021). Existing studies have predominantly focused on evaluating DSTs through technical assessments or by using questionnaires and surveys to understand the end-users' experiences and challenges (Akaka et al. 2024; Dzalbs et al. 2023; Nicholson et al. 2020). These studies are primarily based on literature reviews or on a limited number of specific tools to identify the drivers of DST adoption and solutions. Rarely has a participatory approach been employed to identify challenges, potential improvements, and recommendations to accelerate the adoption of DSTs. This represents a missed opportunity, as participatory approaches involving multi-stakeholder workshops are crucial for engaging end-users and addressing knowledge gaps, as well as accommodating the diverse agricultural contexts and needs.

This study aimed to employ a participatory approach to gain insights into the adoption and scaling challenges of DSTs across various agricultural contexts, as well as to develop recommendations. The participatory approach involved multi-stakeholder workshops conducted in diverse agricultural contexts. The objectives were to:

- Discuss the outcomes of the stocktake on DSTs of the previous study.
- Explore the use of decision-support tools across various agricultural contexts.
- Identify the different challenges and barriers to adopting the DST.
- Outline potential strategies and recommendations according to stakeholders to develop more attractive tools and to identify opportunities for scaling DST across Europe.

2 | General Approach and Workshops Methodology

Multi-stakeholder workshops were conducted in four countries to address the unique agricultural, environmental, and socio-economic conditions that vary across different agricultural contexts. By involving a diverse stakeholders, including farmers, advisors, DST developers, researchers, and policymakers, the workshops enabled the identification of local, context-specific challenges and opportunities for the adoption of DSTs. They also allowed for the exploration of shared and unique insights and perceptions regarding the subject. At the social level, shared negative perceptions slow down the adoption of DSTs, creating barriers to their diffusion across agricultural systems (Markard et al. 2016; Moretti et al. 2023). By defining the similarities and differences in stakeholders' perceptions of DSTs and the actions that should be undertaken, a common ground can be established to further guide system development (Moretti et al. 2023).

The multi-stakeholder workshops were conducted in Sweden, Latvia, Italy, and Turkey, capturing the diverse agricultural conditions across Europe and Turkey. A diverse representation of stakeholders was considered to ensure a wide range of perspectives and insights. We engaged a mix of participants, including end-users, individuals from development and research backgrounds, and policymakers. For each workshop, farmers were selected to represent their specific regions within each country. Overall, the farmers invited to the four workshops represented a broad spectrum of end-users, ranging from non-adopters to early adopters, thereby capturing the varied needs and socio-economic aspects in Europe and Turkey. Farmers and advisors were the main participants, except for the workshop in Latvia, where policymakers and representatives from farmers' unions were also invited, providing additional perspectives. Participation was as follows: Sweden (21 participants), Latvia (23 participants), Italy (25 participants), and Turkey (32 participants). The types of stakeholders participating varied across the four workshops and are described in Table 1.

The workshops were conducted in person in all countries, except for Italy, where it was conducted online. Each workshop was carefully designed and structured to facilitate discussions, with three sessions aimed at gathering input, promoting dialogue, and synthesising outcomes. The workshop script was followed in all four workshops. Certain elements of the discussions were conducted differently and by stakeholder type in some workshops, providing additional insights into the results. Figure 1 shows the structure of the workshops, key activities, and the analytical framework, highlighting the format employed in each workshop (the workshop script is detailed in the Supplementary material).

In the first session, the results of a previous stocktake study on DSTs across Europe were presented to establish a common foundation for discussion and to contribute any additional information. This stocktake study (Warren Raffa et al. 2025; Räsänen et al. 2024) covered expert views (mostly by researchers) on the DST availability and use across 18 countries in Europe, including Turkey. The study focused on DSTs related to nutrient use efficiency, soil organic carbon, and soil water retention, and it evaluated the use of 115 digital DSTs, revealing limitations as well as future development needs, with an emphasis on soil health. This provided the background for the workshops that aimed to expand upon the stocktake findings through a more inclusive participatory approach involving a diverse array of stakeholders. During each workshop, participants were asked to review a list of tools commonly used in their country and to complete the list by adding any missing tools. Regarding soil-related challenges, a list was also provided, allowing them to add any relevant challenges specific to their region or country. At each workshop, participants voted on what they considered to be the main challenges in their specific context. For our analysis, the ranking was determined based on the number of votes, with rank 1 assigned to the challenge receiving the highest number of votes, indicating it as the most significant issue. In cases where challenges were not voted on by participants, we interpreted this as an indication that they were not considered major issues in their context.

TABLE 1 | Stakeholders' participation at the workshops in Italy, Latvia, Sweden and Turkey.

Stakeholders	Italy	Latvia	Sweden	Turkey
Farmers	9	2	11	12
Advisors	7	2	2	7
DST providers	1	4	4	1
Researchers	5	9	4	12
Farmers union representatives	2	2	—	—
Policy-makers	1	4	—	—

The second session was the core of the workshops, during which participants were divided into three smaller, multi-stakeholder groups. Each group included representatives from key stakeholder categories. Discussions were structured around several key topics regarding DSTs desired and missing features, the information needed to make informed decisions, and potential solutions for the adoption of DSTs. In this session, participants were provided with a list of DSTs features to rank and indicate which features were lacking. At the workshops in Italy, Sweden, and Turkey, participants selected the most important DSTs features for discussion and completed the missing ones. On the other hand, participants at the Latvian workshop chose to identify both the most and least important features. Additionally, participants received three statements for discussion: i) all tools should have a smartphone app, ii) DSTs should provide information on environmental impact, and iii) DSTs must be flexible and take actual weather conditions into account.

The final session included a plenary discussion aimed at synthesising diverse perspectives and identifying common themes and recommendations for the future improvement and implementation of DSTs.

Reports were generated for each workshop. To achieve our overall goal, we analysed the outcomes of the workshops using an analytical framework structured around three levels: (1) the objectives and current use of DSTs and the local soil-related challenges that affect the adoption of these technologies; (2) the specific and common challenges encountered in adopting DSTs across various contexts, taking into account different dimensions of the adoption process; and (3) potential improvements and solutions to promote the adoption of DSTs. The analytical framework used during the workshops is shown in Figure 1.

3 | Results and Discussion

3.1 | The Objectives and the Current Use of Decision-Support Tools for Soil Management Perceived by Stakeholders in Different Contexts

A total of 42 decision-support tools (DSTs) were identified by farmers and advisors for soil management, with a focus on soil water availability and retention, nutrient use efficiency, and soil organic carbon.

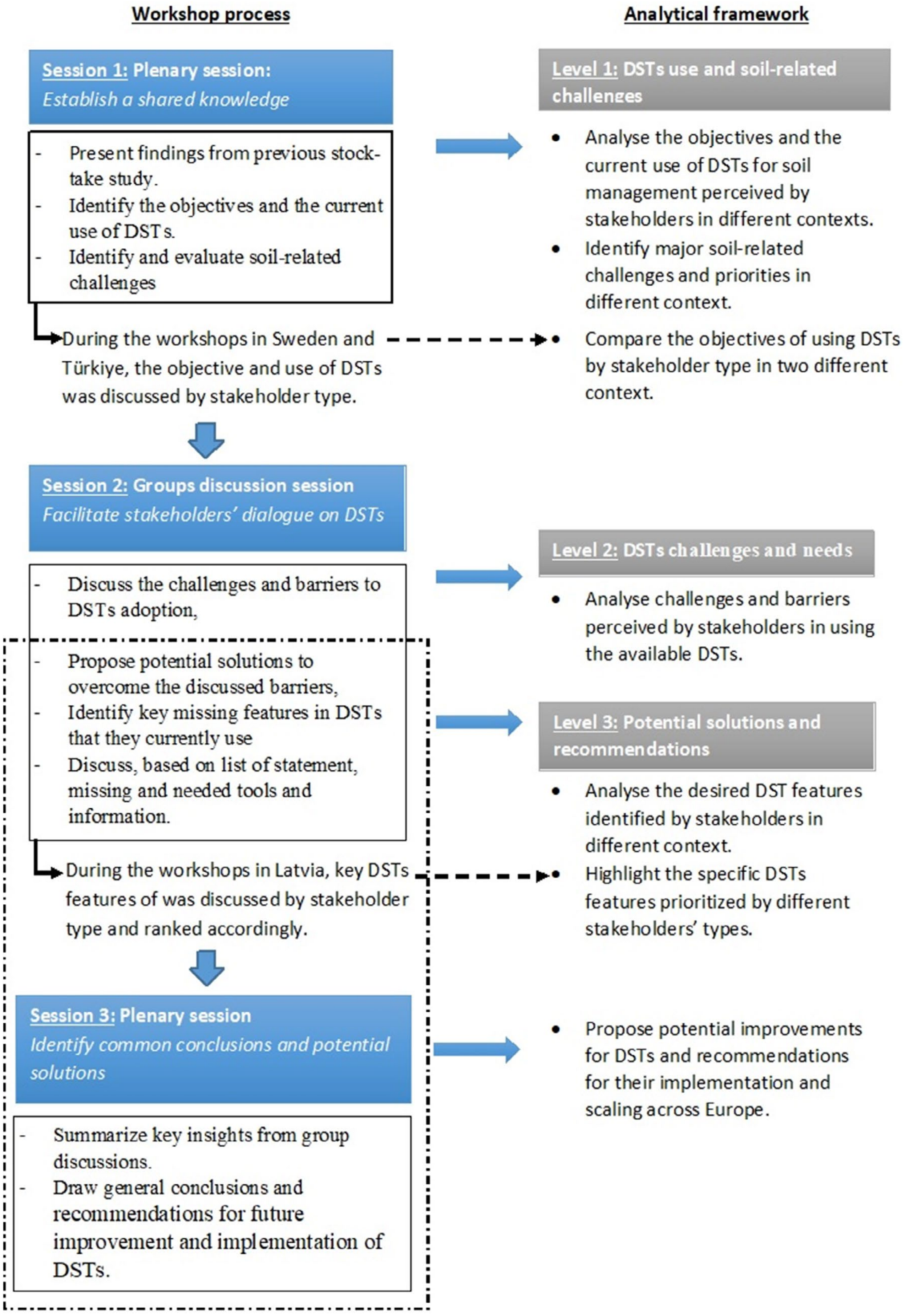

FIGURE 1 | Methodology: workshops workflow and analytical framework.

Table 2 presents the main DSTs used to manage the three parameters in Latvia, Italy, Sweden, and Turkey. The findings revealed significant differences in the use of DSTs across these countries. In Sweden, Latvia, and Turkey, participants identified tools that are parameter-specific, with each DST addressing only one of the three parameters. In contrast, participants

TABLE 2 | The decision support tools used to manage nutrient use efficiency, soil organic carbon, and soil water availability and retention in Italy, Latvia, Sweden, and Turkey.

Soil parameters	Italy	Latvia	Sweden	Turkey
Soil nutrient use efficiency[a]	—	• AgriPORT • Yara Atfarm • Linas Agro Tools • Agrochemical analyses • ONESOIL app • NEXT FARMING digital system • Electronic Application System of the national rural support service	• Yara Afarm • Yara N-sensor • Yara Checkit • Yara nutrient calculation tool • CropSat • Kvävevågen • Gödselkalkylen • Vera • Greppa Växtnäringsbalans på nätet • Soyl • Solvi • Dataväxt app • Näsgård mark • Markkartering.se	• Onesoil • SoilScanner • Doktar IoT Solutions • Gübretaş fertilisation guide
Soil organic carbon[a]	—	—	• Odlingsperpektiv	• Digital soil analyser
Soil water availability and retention[a]	—	• Sensors • Local weather stations	• Vattennivå i brunn • Raindancer • Soil Moisture Sensor • P–T Soil Station service • Hur mår min jord?	• Meteos • TAGEM SuET • AquaCrop • Filiz& Filizpro • AgroCares Digital Soil Analysis Device
Integrated tools[b]	• vite.net • granoduro.net • Elaisian	—	—	—

[a]Single tools (one parameter).
[b]Integrated tool incorporating three parameters (soil nutrient use efficiency, soil nutrient use efficiency and soil water availability and retention).

in the Italian workshop reported the use of integrated tools, with each tool designed to address all three parameters within a single tool.

In Italy, several large and medium-sized companies involved in industrial crop production currently utilise DSTs to manage their fertilisation and plant protection plans, as well as to optimise crop nutrient use efficiency. In contrast, small and very small companies or farms face greater challenges in implementing DSTs. Furthermore, some large companies employ Decision Support Systems more frequently than DSTs, particularly in relation to water and nutrient management. However, DSTs are less commonly used to monitor SOC, highlighting the need to develop appropriate DSTs focused on the application of carbon farming.

In Latvia, stakeholders emphasised that the main objectives of using DSTs in soil management are as follows:

i. To control nitrogen fertilisation doses to save money and prevent unnecessary application of fertilisers to fields,

ii. To use soil agrochemical analyses for monitoring the general condition of the field, as well as to comply with regulatory requirements.

iii. To control soil pH and plan liming and to be able to apply for financial support,

iv. To use GPS systems in the field to bypass obstacles and accurately draw boundaries between fields,

v. To monitor the development of the crop and the health of the plant,

vi. To improve the efficiency of work planning.

In Sweden, DSTs were mainly developed to manage soil nutrient use efficiency, whereas in Turkey, they are mainly used for managing soil water availability and retention (Table 2). The differing applications of DSTs reflect the distinct priorities and challenges present in each agricultural context. Table A1 (in Supplementary material) summarises the various objectives discussed by stakeholders during the two workshops in Sweden and Turkey. Although the adoption of DSTs is more advanced in Sweden than in Turkey, farmers in both countries expressed similar priorities: increasing yield and production quality, optimising fertilisation and irrigation, and improving soil management. This alignment of objectives across different contexts suggests that, despite varying levels of technological implementation, there is a shared recognition of the potential benefits of DSTs. Swedish farmers, in particular, expressed interest in field-level estimates of soil nitrogen mineralisation, detection of nutrient deficiencies, and controlling distribution between fields. Advisors, on the other hand, from both countries emphasised that the objectives of DSTs are to make daily work easier, improve profitability, and ensure compliance with regulations. Additionally, advisors in Turkey viewed DSTs as a means to bridge the information gap and raise farmers' awareness of sustainable agricultural practices. DST providers shared the same priorities as farmers, while researchers introduced additional objectives, including yield forecasting and improved timing of fertilisation. These results underscore the varying perceptions of the usefulness and ease of use of DSTs among different stakeholder groups, which align with key elements of the Technology Acceptance Model proposed by Davis (1986). By considering stakeholders' perceptions, the adoption and acceptance of DSTs can be enhanced, ensuring that the tools meet the needs and expectations of farmers and advisors in diverse agricultural contexts. These findings suggest, on one hand, that there are common needs across different contexts, and on the other, a clear alignment of DSTs with specific local agricultural needs that shape how these tools are used and developed.

To further analyse the relevance of the available DSTs, stakeholders identified the major soil-related challenges in their regions (Table 3). The findings illustrate the variation in priorities assigned by stakeholders in each country, thereby revealing the diversity of soil management challenges faced. The major soil-related challenges identified were soil compaction, soil fertility, climate adaptation, soil organic matter, and soil water management. Notably, soil compaction emerged as a significant issue in Sweden, where it was ranked as the highest priority, followed by soil organic matter and water availability. Soil organic matter was consistently prioritised across the four countries, where it was ranked the highest in Italy and Latvia. However, the underlying reasons for this prioritisation are likely to differ. In Italy, low levels of soil organic matter, due to intensive agriculture and climatic conditions, make its management a critical concern. In contrast, Latvia has a high proportion of organic soils, which necessitates a different approach to SOM management. These differences also account for the variation in soil fertility rankings. Only in the Italian workshop, soil fertility was identified as a top priority, where the term 'Soil fertility' was intended by several participants as comprehensive of soil biodiversity, thereby ranking it as the highest concern. This raises the question of how soil fertility is defined and perceived by different stakeholders. Water availability was ranked as a major challenge in Italy and Sweden. However, during the workshop in Turkey, stakeholders prioritised soil water management and climate adaptation challenges. In the context of climate change, water availability is a major concern in Turkey, making soil water management a critical issue. This underscores the need for an effective DST tailored to soil-water management, which requires a deep understanding of soil properties at both the field and farm levels.

TABLE 3 | Soil-related challenges priorities in Italy, Latvia, Sweden and Turkey based on stakeholders.

	Italy	Sweden	Latvia	Turkey
Soil compaction	4	**1**	5	4
Soil fertility	**1**	3	3	3
Climate adaptation	3	3		**1**
Nitrogen use efficiency		3		
Soil organic matter	**1**	2	**1**	2
Water availability	2	2		
Soil erosion			4	4
Acidification			2	
Soil water management				**1**

1: Most important challenge.
5: Least important challenge.
No score: Not rated.

The nitrogen use efficiency was assessed only in the Swedish workshop (Table 3), underlining the particular importance of nutrient management in the Scandinavian region. Over-spreading of nitrogen can lead to a significant risk to water quality. However, the relatively low average ranking of this issue (ranked 3) may reflect the availability of reliable DSTs in Sweden that support efficient nutrient management (Table 3). This also indicates that stakeholders in Sweden trust the effectiveness of the available DSTs. In summary, the findings indicate that the allocation of priorities reflects local variations in environmental issues, as well as the need for tailored DSTs to address these multifaceted, context-specific challenges. Furthermore, it underscores the importance of developing DSTs that respond to the unique conditions of each agricultural context. According to Rogers (2003), innovation-diffusing theory, technology adoption depends on local context, needs, and specific conditions. By addressing these factors, the relevance and usability of decision-support tools can be enhanced.

3.2 | Challenges and Barriers Perceived by Stakeholders of Using the Available DSTs by Farmers and Advisors

In the second session of the multi-stakeholder workshops, the discussion focused on the challenges involved in promoting the use of DSTs by farmers and advisors and revealed the main barriers that affect their implementation and scalability. Table A2 (in Supplementary material) outlines the categories of challenges, which were defined based on stakeholder responses. The main challenges identified include: 19% related to user factors, 12% concerning economic costs and viability, 19% associated with technological complexity, 12% regarding compatibility issues, 8% related to marketing, 12% about technical issues, and 19% related to the scope of application of DSTs.

Stakeholder discussions emphasised that aspects related to farmers, such as education level, age, and traditional agricultural knowledge, significantly influence the adoption of DSTs. During the workshop in Latvia, participants noted that many farmers often do not trust the tools' results, especially farmers with up to 200 ha of land, do not see the benefit of using DST. Indeed, DSTs may fall within the latitude of rejection for some farmers if they do not align with their established practices or if the perceived benefits are unclear (Sherif et al. 1965). A similar concern was raised during the workshop in Turkey. In Italy, medium, small, and very small farms have more difficulties in using DSTs, besides the average age of farmers, who may not be always so friendly with digital tools. The adaptive capacity of farmers, including differences in skills, investment ability, and age, can enable some farmers to take advantage of agricultural technologies more effectively than others (Bucci et al. 2019; Paustian and Theuvsen 2017). To promote broader adoption, developers of DSTs should design technology that is better suited to the needs of smaller-scale farmers (Rose et al. 2023). Ultimately, this highlights the importance of aligning technology with farm characteristics and ensuring it meets users' needs and capabilities.

A prominent challenge highlighted in all of the workshops was the complexity of the technology as a major barrier to its implementation. Learning all of the possibilities offered by new technology and how to navigate between the different features requires time. Additionally, high levels of errors in using the tool due to a lack of technical knowledge may affect the farmers' trust in the technology (Kshetri 2014; Ofori and El-Gayar 2021). The complexity of some technologies could even be perceived as a factor that can create difficult working conditions (Nowak 2021). Therefore, it is crucial to consider the daily interactions between farmers and the technology and how farmers experience technology on the farm (Rose et al. 2023). Compatibility issues between the DSTs and the farmers' technologies and conditions were also raised. These issues, which can occur between new tools and older technologies or even between different versions of the same tool, were notably discussed during the workshop in Sweden. Additionally, poor internet connection in rural areas can affect the effectiveness of DSTs, making it challenging for farmers to use these tools in day-to-day operations in the field.

Another barrier highlighted in the four workshops is the lack of transparency regarding the calculations of recommendations. Stakeholders emphasised the importance of farmers and advisors being able to assess whether the recommendations are suitable for their specific farm conditions and whether they can modify the tool's settings. This transparency is essential for ensuring trust in the reliability and accuracy of DST outputs.

Although the challenges mentioned above, such as farmers' knowledge gaps, technological complexity, compatibility issues, and transparency, could potentially be mitigated with effective support systems, the lack of sufficient technical support was another concern highlighted by stakeholders. Moreover, the economic costs and viability of using DSTs remain significant barriers. The costs associated with investing in new technology, purchasing and maintaining hardware and software, updating tool licences, as well as obtaining and analysing the data and the feasibility of the recommended results make farmers question and doubt their decisions to adopt and experiment with new technologies (Ofori and El-Gayar 2021).

While technical and cost barriers were key concerns, stakeholders also identified a lack of efficient marketing and visibility gaps as major limiting factors for the adoption of DSTs by farmers. This issue was raised only during the workshops in Latvia and Turkey, as one participant in Latvia stated: 'The problem in Latvia is that there is a lack of marketing for DSTs so there might be many tools that farmers simply do not know about'. This issue may be related to the marketing strategy. According to Paustain and Theuvsen (2017), marketing activities are more likely to succeed if the target farmers are clearly identified. Finally, stakeholders across all workshops underscored the limited scope of current DSTs, underlining the need to broaden their scope in future development.

All the challenges outlined above were shared by stakeholders across all four countries, with the exception of the lack of efficient marketing and visibility gaps, which were particularly emphasised during the workshops in Latvia and Turkey. This highlights both the common challenges in implementing DSTs for sustainable soil management and the fact that some barriers may be more pronounced in specific contexts. These challenges are particularly relevant for smallholder farmers, especially those who are older or less educated, as they may struggle with new technologies due to perceived complexity, limited access to information, or doubts about the usefulness of the tools (Davis 1986; Rogers 2003). Additionally, external factors, such as institutional and social structures, networking, policies, the market, and the role of extension services, can add another layer of complexity to the adoption process. According to Leeuwis (2004), communication and learning processes can help overcome these barriers. Interactive and tailored communication strategies can facilitate awareness, adoption, and support the learning process, ultimately supporting the successful integration of new technologies.

3.3 | Stakeholders Needs and Interests in More Effective and Attractive Decision-Support Tools

3.3.1 | The Key Desired Features of Decision-Support Tools According to Stakeholders

Table 4 summarises the stakeholders' responses regarding the desired features for DSTs at the four workshops. The responses highlighted both common and differing priorities, as well as the expected features for users in the four countries. Among the features identified across all workshops, time efficiency, reliability, field calibration, accessibility, inclusivity, ease of use, and automated data acquisition were identified as the most required and desired features in DSTs. Stakeholders stressed the critical need for DSTs to deliver real-time information to facilitate timely decision-making. The desire for time-saving tools for farm planning at both field and farm levels further emphasises the importance of DSTs in supporting the efficient management of daily farming activities. This reflects the fact that the success of innovations depends on their availability, affordability, and profitability, both in terms of cost and time (Rosenzweig and Foster 2010).

Stakeholders stressed the importance of the tools to be science-based in order to provide reliable outputs and avoid misinterpretation of the results, which could lead to poor crop management and negative environmental impacts. Consequently, tools calibrated

TABLE 4 | Stakeholders' responses to the desired features for decision-support tools at the four workshops: Italy, Latvia, Sweden, and Turkey.

Features	Case studies	Details/explanation
Time efficiency	Turkey, Italy, Sweden and Latvia	• Delivers results that are easy to apply in real time and in the right time. • Do not require too much time to work on it. • Save time in planning.
Reliability and field calibration	Turkey, Italy, Sweden and Latvia	• Reliable results based on science. • Calibration on farms in the area.
Accessible and inclusive	Turkey, Italy, Sweden and Latvia	• Provides easy access to information. • Open to everyone. • Accessible support service. • Easily accessible both in terms of cost and hardware requirements.
Easy use/simplicity meets flexibility	Turkey, Italy, Sweden and Latvia	• User-friendly interface. • Do not require much information. • Flexible tools.
Automated data acquisition, collection and storage	Turkey, Italy, Sweden and Latvia	• Default access to available regional databases and farm data, instead of manual data-entry.
User-driven design/co-designed with the end user	Italy and Turkey	• User involvement in the design process.
Farm management dashboard for a better farming	Latvia and Turkey	• Provides benefit in production planning. • Consider yield quality. • Efficient use of natural resources and enable fertilisers and water saving. • Monitor crops development and health
Environmental assessment of agricultural practices and scenarios	Turkey	• Raise awareness for sustainable farming. • Enable farmers to change their practices to more environmental-friendly farming systems.
Empowering farmers through knowledge: learning and guiding tools to become a better farmer	Turkey	• Making it easier to be a farmer. • Inform and guide. • Provide statistical support and automatic interpretation. • Help farmers to learn and make decisions in situations where users cannot make decisions.

to local farm conditions were identified as crucial for ensuring both the accuracy of recommendations and their relevance to specific farming contexts, as well as their effectiveness across diverse agricultural settings. Moreover, stakeholders requested more intuitive, flexible, and user-friendly tools. Farmers generally prefer tools that require minimal learning time and can be easily integrated into their daily farming practices (Rose et al. 2016). The use of complex inputs or overly detailed results can create confusion and inefficiencies. Stakeholders suggested that graphical visualisations could effectively present results in a simplified and comprehensible manner, enabling farmers to make informed decisions without becoming overwhelmed by information (Zhai et al. 2020). Automated data acquisition emerged as a key feature for reducing the complexity of DSTs. However, this requires collaboration among various parties and sectors. Balancing these aspects, meeting the reliability of science-based tools while maintaining simplicity, is challenging but necessary for the future development of DSTs. Achieving this balance is crucial to ensure that tools remain both technically accurate and accessible to end users. Furthermore, the storage and use of historical data were recognised as valuable features. Historical data can provide valuable information that can improve the quality of future DSTs (Zhai et al. 2020) but also help farmers in assessing the effectiveness of their practices by comparing inputs and outputs over time.

While common features were shared across the workshops, notable differences in desired features were also observed. Stakeholders in Italy and Turkey stressed that the DSTs should be developed in collaboration with end-users to ensure that the tools effectively meet their needs. While at the workshops in Latvia and Turkey, participants suggested that a Farm Management Dashboard is a desirable feature, as it would provide more comprehensive information regarding production planning, yield quality, input use efficiency, and the monitoring of crop development and health. Additionally, stakeholders at the workshop in Turkey highlighted the potential of DSTs to enhance sustainable agricultural practices and raise farmers' awareness of the environmental impacts of their activities by empowering them with knowledge and providing learning and guiding tools.

TABLE 5 | Participatory assessment of decision support tool features by different stakeholders during the workshop in Latvia:

Features	Farmers	Advisors	DST providers	Researchers	Policy- makers/ farmer union representatives
Easily accessible both in terms of cost and hardware requirements.	Dark grey	Dark grey	Light grey	Dark grey	Dark grey
Reliable science-based results and calibration on farms in the area.	White	Dark grey	Dark grey	Dark grey	Dark grey
Results easy to apply in real time.	Dark grey	White	Dark grey	Dark grey	Dark grey
Developed in collaboration with users.	White	Light grey	Light grey	Light grey	Light grey
Clear visualisation of results.	Light grey	White	White	Light grey	Light grey
User-friendly interface.	White	Light grey	White	Light grey	Light grey
Doesn't require much information from me.	Light grey	White	White	Light grey	White

Note: Dark grey: Most important, light grey: Least important, white: Not considered by participants.

During the workshop in Latvia, participants were able to rank the proposed DSTs features. Two interesting findings shown in Table 5 are as follows:

i. farmers considered only 'Easily accessible' both in terms of cost and hardware requirements and 'Results easy to apply in real time' as important features,

ii. DSTs developers did not consider 'Clear visualization of results', 'User-friendly interface' and 'Doesn't require much information from me' features in the evaluation.

These results raised questions about the choices and priorities made by DST developers, particularly in balancing farmers' desired features with tool reliability and accuracy. Farmers assess the potential of DSTs based on factors such as ease of use, cost-effectiveness, and perceived benefits. This emphasises that the adoption of DSTs is not only driven by technical functionality but also by the benefits and practicality of the tools, which can shape farmers' perception of adopting them (Monteleone et al. 2020). Understanding the decision-making process from the end-user's perspective is crucial for the development of effective DSTs. A cross-country analysis of the four workshops revealed that stakeholders shared two main concerns. First, the tools must be user-friendly and accessible, with minimal learning time, intuitive interfaces, and low cost; and second, DSTs must be locally calibrated, providing real-time and scientifically based results, adapted to specific context and farm conditions and aligned with the needs of end-users. These concerns underscore the need to balance technical accuracy with ease of use to support adoption and effective decision-making in diverse agricultural contexts.

3.3.2 | The Role of Smartphones Perceived by Stakeholders in Fostering Using DSTs in Agriculture

Integrating DSTs into smartphone applications represents both an opportunity and a challenge for increasing sustainable agricultural practices. Previous studies have explored the potential of using a smartphone in agriculture (Dehnen-Schmutz et al. 2016; Mendes et al. 2020; Michels et al. 2020; Tobiszewski and Vakh 2023). The workshop's findings further highlighted how farmers and stakeholders recognised both the benefits and limitations of mobile access to these tools.

According to farmers from Latvia, different tools should be integrated into a single platform while ensuring that the most important functions are also available on a mobile app. The mobility provided by smartphones was seen as a key advantage, allowing farmers' access to real-time information and facilitating quick decisions. Similarly, policymakers and representatives from farmer unions also noted that DSTs on smartphones facilitate more efficient farming and enable real-time changes and adjustments. During the workshops in Turkey and Italy, stakeholders noted that smartphones could promote more frequent use of DSTs by farmers due to their practicality. Italian farmers, for example, were interested in DSTs on a mobile app that gives prompt alerts about adverse weather events to implement timely mitigation actions. Given the relatively low adoption of DSTs in Turkey, the role of smartphones was appreciated more during the workshop in Turkey to foster the use of DSTs among farmers, given the practicality of the device in the field and its potential use as an alert system.

Despite these benefits, workshop participants emphasised that smartphones should not be viewed as a one-size-fits-all solution. While many farmers appreciate the portability and the advantages of smartphone-based DSTs, DST providers, advisors, and researchers pointed out several limitations. They argued that farming is too complicated to be managed entirely through a small screen. Working on maps and data analysis is more convenient on a larger screen; besides, databases and programs are more easily available on the computer. Additionally, differences between iPhone and Android systems can affect DST accessibility and usability. Michels et al. (2020)) noted that new apps are generally launched first on Android, likely due to a simpler application's approval process on Google Play. Similar concerns were raised in the Swedish workshop, where stakeholders emphasised that using the tools as smartphone apps depends on the type of tools and on how quickly the information is needed.

Despite these challenges, the participants highlighted the growing interest and acceptance of smartphones for DSTs among farmers. Smartphones' portability and ease of use make them convenient for quick decision-making, real-time monitoring, and receiving alerts. Their application in agriculture is a promising tool to make managing soil quality easy, user-friendly, and less time- and cost-consuming (Tobiszewski and Vakh 2023). Yet, computers remain essential for in-depth data analysis and more complex advisory services. These findings underscore the need for a complementary, two-tiered DST system, where different users require varying levels of functionality, and different devices serve distinct purposes based on their needs.

3.3.3 | Can Decision-Support Tools Help to Increase the Awareness of Environmental Impacts of Agricultural Systems?

DSTs have the potential to enhance environmental awareness in agricultural systems. Insights from the four workshops consistently underscored the relevance of integrating environmental dimensions into these tools. Participants pointed out that environmental considerations are mandatory due to EU regulations and enable the balancing of environmental and economic goals. However, they stressed that such integration must be based on a solid scientific base to ensure credibility and usefulness.

At the workshop in Turkey, stakeholders emphasised that the negative or positive effects of the practices and inputs on the environment and ecosystem should be monitored. They suggested that DSTs could provide warnings regarding environmental risks, such as the potential economic damage caused by pests and diseases, and provide tailored management strategies. However, at the Swedish workshop, opinions were divergent. While participants agreed that the environmental sustainability of agricultural production is important in Sweden, concerns were raised about the risk of overcomplicating DSTs by adding too many environmental features, potentially reducing their effectiveness and use. Participants also expressed that environmental considerations and awareness should involve consumers and the market and be included in the measures for the environmental labelling of products.

Workshops findings indicated the potential of DSTs to bridge the gap between farmers' environmental awareness and practical agricultural decision-making in the field and to contribute to European sustainability goals, such as the Green Deal. However, environmental benefits were not always considered by farmers as the unique important reason for adopting technologies (Paudela et al. 2020).

Some stakeholders consider DSTs as essential for helping farmers navigate the trade-offs between profitability and sustainability, while others are concerned about the tool's ease of use and its acceptance by the farmers, advisors and the market. A study on the adoption of nutrient-reducing technologies in five Baltic Sea countries indicated that global environmental concerns do not affect decision-making, while farm-specific environmental concerns such as soil quality may have a significant influence (Konrad et al. 2019). Therefore, connecting the environmental impacts of soil management at the farm scale with global impacts can help farmers to better understand these environmental impacts and encourage more sustainable practices and agriculture. Yet, the challenge for future development lies in integrating comprehensive environmental assessments without compromising the tool's user-friendliness.

Finally, this study highlights the knowledge gaps in the practical use of DSTs and the importance of local agricultural conditions, environmental and socio-economic aspects, in shaping how these tools are used and adopted. DST adoption is not a straightforward decision but involves complex pathways, including varying levels of awareness, trial, use and dis-adoption over time (Tey and Brindal 2022). Therefore, a one-size-fits-all solution is not a sustainable approach to effectively fulfil the needs of stakeholders across different contexts.

3.4 | Recommendations for Fostering Implementation and Successful Scaling of Decision-Support Tools Across Europe

The recommendations made by stakeholders at the four workshops, in Italy, Latvia, Sweden and Turkey, are summarised in Table 6. The recommendations can be categorised as follows: (i) most common (if it is emphasised in the three workshop or more), (ii) moderately common recommendation (if it is emphasised in two workshops) and (iii) specific recommendation (if it is raised in only one workshop). The four workshops resulted in a total of 22 proposed recommendations. However, the extent to which these recommendations were addressed varied across workshops: 59% were covered in the Italian workshop, 55% in the Swedish workshop, only 27% in the Latvian workshop, while 73% were covered in the workshop in Turkey. These results highlight the diversity of issues that need to be addressed and the varying challenges faced across different contexts. For instance, cultural differences with respect to openness to new technologies could explain possible different adoption between regions of interest (Michels et al. 2020).

Stakeholders proposed a set of tailored actions to be implemented that consider different aspects to effectively address the different layers involved in the adoption process and scaling of DSTs. A set of recommendations (R1–R9) emerged from the considerations suggested by stakeholders during the four workshops, and the analysis of the various challenges and potential improvements discussed above. Nine recommendations detailed below were formulated to match the stakeholder's needs, objectives, and challenges. While certain recommendations were commonly emphasised across multiple workshops, no single recommendation was universally prioritised in all four countries. This underscores the need for context-specific approaches rather than a one-size-fits-all solution. The nine recommendations proposed (R1–R9) address key challenges identified by

TABLE 6 | The recommendations made by stakeholders at the four workshops: Italy, Latvia, Sweden and Turkey.

Recommendations responses	Italy	Latvia	Sweden	Turkey
Tools positive results demonstrations		x	x	
Open-source decision support tools	x	x		x
Accessible technical support and training		x	x	x
Simple and practical decision support tools	x	x		x
Real-time results	x		x	x
Ensure high efficiency and accuracy	x	x		x
Data set is up-to-date				x
Use field data for tools optimization	x			x
Artificial intelligence supported				x
Be able to work in areas without internet reception				x
Affordable tools	x		x	x
Correct calibration	x		x	x
Automatic selection of reliable satellite images			x	x
Impact assessment of applications			x	x
Transparent tools			x	
Easy to work with on data and results	x		x	x
Consider more crops and organic farming	x		x	
Indication of what measures are required and useful for a specific situation.			x	
DST should have default access to available databases	x	x	x	
Co-designed with the end users	x			x
Tools should address the calculation of farm carbon footprint	x			
DST could give very useful alerts to farmers.	x			x

stakeholders, but their effectiveness may vary depending on regional conditions and locally specific adoption barriers.

3.4.1 | Recommendations for end-users: Farmers and advisors

R1. Ensure tool's user-friendliness.

To expand the range of end-users and enhance uptake, improve their satisfaction while ensuring the transition toward sustainable soil management practices.

- *Prioritise simplicity, accessibility, and flexibility in design*: User-friendly, intuitive, and easy-to-navigate DSTs for users may enhance usability even for older farmers or those less accustomed to digital tools. The use of smartphones in agriculture can play a big role in the adoption of DSTs for soil management by making them more user-friendly, time-efficient, and cost-effective (Tobiszewski and Vakh 2023). The complexity of currently available technologies is one of the most common challenges for DST adoption (Ofori and El-Gayar 2021). Therefore, by integrating simple and adaptable features into the design, developers can ensure that DSTs meet the practical, everyday needs of farmers, ultimately increasing their utility and value.
- *Support a wide range of crops and organic farming practices*: Expanding the scope of application of DSTs to include a wide range of crops and farming practices, including organic farming, extends the reach to a wider range of farmers.
- *Enable offline functionality for remote use*: This feature allows farmers to manage their farms efficiently without connectivity issues, ensuring the tool's practicality and usability by farmers in even the most isolated areas.

R2. Balance reliable outputs of DSTs and the tool's user-friendliness.

To improve the end-user experience in using DST while guaranteeing its reliability and scientific basis.

- *Balancing a reliable science-based tool with simplicity*: This is challenging but essential for the future development of DSTs.
- *Utilise automatic selection of reliable, cloud-free satellite images*: This feature reduces the burden on users to manually

sift through large datasets or identify potential data inconsistencies. This feature could improve the tool's performance, use, and the quality of the outputs and recommendations.

- *Eliminate redundancies and focus on relevant information*: It is necessary to simplify the user's decision-making process and the complexity of the tools. This enables users to act quickly and make accurate, rapid decisions. This concerns the outputs and recommendations that will be used mainly by farmers and would expand the range of users with different backgrounds, ages, and levels of education to make accurate decisions under complex conditions.

R3. Integrating economical and environmental features in new DSTs.

To balance environmental goals with economic profitability in their decision-making.

- *Develop features to reduce production costs:* Making farming more economically sustainable.
- *Include carbon footprint calculation*: Integrate features to calculate and monitor the farm's carbon footprint, contributing to sustainability efforts.

3.4.2 | Policy-level recommendations for broader scales

Recommendations to address broader policy measures needed to guide implementation, support policy-driven actions, and ensure DSTs are available to all in different agricultural contexts.
R4. Ensure inclusivity, accessibility, and usability for all users.

Ensuring affordable access to DSTs: Could reduce the financial barriers, making them more attractive, especially for small-scale farmers. By addressing the specific needs of smaller farms, less high-tech-oriented farmers and non-adopters, open access and cost-effective designs will help bridge the gap between early adopters and those slower to embrace new technologies, fostering a more inclusive agricultural innovation ecosystem (Paustian and Theuvsen 2017).

R5. Facilitating innovation process and the implementation of interdisciplinary approach through co-creation platforms.

To drive end-users' engagement and acceptance of new technology and DSTs.

- *Demonstrate effectiveness through real-world success stories and building social cohesion with technologies*: Positive examples of success in similar contexts can validate the tool's value and promote a shared understanding of the value and the challenges faced. The alignment of perception related to the tools enables the building and fostering of social cohesion with technologies, creating a high level of trust among farmers (Moretti et al. 2023; Rogers 2003; Thar et al. 2021).
- *Offer comprehensive support and capacity building*: Delivering robust technical support and training programs, potentially enhanced by artificial intelligence, enables users to take full advantage of the tool's capabilities. Studies suggested that smallholders and other farmers often prefer learning environments that involve guided discussions, interactive learning and problem-solving rather than prescriptive instructions (Thar et al. 2021). Stakeholders also stressed that AI-driven training might be a great opportunity to enhance farmers and advisors' knowledge.
- *Empower users to contribute to tool optimization and co-design*: This will help to strengthen user commitment and adoption, and to consider users' feedback on tools, as well as their specific needs and the challenges they face. This enables the development of DSTs that are more acceptable to farmers and therefore more likely to be implemented in the field (Queyrel et al. 2023).
- *More research to understand human-technology interaction*: More interdisciplinary and transdisciplinary research is needed to understand how humans interact with DSTs. Some technologies are perceived as complex, which can make them difficult to use. By focusing on human-technology interaction, future research can shape DSTs to be more intuitive, adaptable, simple, and flexible. This also enables the creation of technologies that are both scientifically robust and user-friendly (Steenwerth et al. 2014).

R6. Development of a decision-support tool for monitoring and assessment, scenario analysis, and alert system: multiple-indicators-based DST.

DSTs that incorporate multiple indicators, including artificial intelligence (AI)-based tools, could ensure sustainable soil management at different scales and achieve local, national, and European goals of sustainability.

- *Developing integrated tools to support agricultural decision-making and promote soil health*: Include capabilities for analysing soil conditions, providing essential insights for optimising crop management. A more comprehensive approach to helping farmers make informed decisions about managing soil to improve soil health.
- *Facilitate scenario analysis to support informed decision-making*: Incorporate features that allow farmers to evaluate different scenarios, helping them choose the best options for their specific conditions.
- *Provide quick and efficient access to critical information*: Design the tool to deliver quick and timely information, enabling users to make prompt and informed decisions when needed.
- *Implement an alert system to keep users informed*: Develop an alert system within the tool to notify farmers of important events, changes, or risks, enhancing proactive management.
- *Deliver tailored soil management recommendations:* Tools calibrated on local farms are needed to ensure the reliability of the tool and to provide tailored recommendations. This enhances farmers' confidence in the DSTs outputs.

- *Scalability of solutions and outputs*: The integration of the different scales is crucial to support the decision-making for farmers and other stakeholders, including policy-making. This aspect was highlighted in the workshop as essential to expand the scope of DST to promote more sustainable policies for soil management and soil health.

R7. Data ownership and transparency of the tools, data sharing and database integration.

Stakeholders emphasised the need for the tool to be transparent to help the users understand what lies behind the tool's recommendations. The transparency is required for data sharing and integration. Sharing data, DST inputs, enables users to have access to the needed and updated input data from different sources. It enables easy navigation and integration with various farm-related databases and simplifies data management. As reported by Ofori and El-Gayar (2021), farmers are effectively owners of their data and agriculture will benefit from its own data regulations, like in healthcare and finance. Such regulations should effectively tackle ownership, privacy, security, and transparency in sharing data, highlighting the need for well-defined regulatory frameworks to manage it.

R8. Need for a clear roadmap for stakeholders.

A roadmap for stakeholders is needed to reduce barriers and develop strategic coordination of the initiatives involved, aimed at fostering the adoption and scale-up of DST at national and European levels through co-innovation platforms.

R9. More consideration of regional disparity in policy-making and targeted funding.

There is a clear alignment of DSTs with specific regional agricultural needs and regional environmental issues that shape how these tools are demanded, used, and developed. There is a need for tailored DSTs to address these multifaceted challenges and respond to the unique conditions of each region. However, while DSTs are designed to align with agricultural and environmental goals, their adoption depends not only on technical relevance but also on farmers' ability to adopt them and the financial capacity and support of different regions to implement them effectively. In Europe, there is significant coordination in funding for climate mitigation in agriculture. While there is strong coordination in the funding, the efficiency of the funding has certain challenges and limitations (IEEP 2024). It is required to consider the regional disparity in the funding to make it more efficient, targeting more vulnerable and marginal areas, besides smaller farms and less high-tech-oriented farmers. This helps to establish regional equity in terms of efforts and resources to achieve sustainability objectives at the regional level and consequently at the national and European levels.

4 | Conclusion

The study aimed to investigate the challenges and drivers involved in scaling DSTs for sustainable soil management and in support of promoting sustainable policies in Europe. This was achieved through multi-stakeholder workshops in Italy, Latvia, Sweden, and Turkey, which explored end-users' experiences and challenges across diverse agricultural conditions.

The findings underscore the complexity of adopting and scaling DSTs. While DSTs at present, focusing on nutrient use efficiency, soil organic carbon, and water retention, have great potential to enhance decision-making and support the transition of agriculture toward sustainable soil management practices, their adoption is limited due to a range of factors. The workshop outcomes revealed common needs for using DSTs in different contexts, and a clear alignment between DSTs and specific local agricultural needs that determine how these tools are used and developed. The stakeholders identified barriers ranging from the technical complexity of the tools, data ownership, and limited scope of application to a lack of marketing and visibility gaps of the tools. The need for DSTs to be adapted to the end-user's day-to-day activities was emphasised as one of the most important drivers of fostering adoption. Moreover, the tool's practicality is a key to providing real-time decision-making. Smartphones potential was highlighted by considering their practicality and mobility. The stakeholders identified different solutions and recommendations to make DSTs more attractive for farmers and provide decision-makers with critical technical, economic, and social considerations to foster DST adoption and scaling in Europe.

The study further revealed that the use and adoption of DSTs vary across countries, with different local priorities and agricultural challenges. Adoption barriers and preferred DST features also differ by region, highlighting the need for adaptable, context-specific DST strategies that address local agricultural needs and promote broader adoption.

Scaling DSTs across Europe can support the transition of agriculture toward sustainable soil management practices and meet the European environmental goals for sustainable agriculture and soil health. However, making DSTs more attractive to end-users while balancing user-friendliness and reliability is a challenge. Future studies should explore participatory and co-design methods for developing DSTs to consider end-user needs and improve human–technology interaction.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.