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Agricultural Decision Support Tools in Europe: What Kind of Tools Are Needed to Foster Soil Health?

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ABSTRACT

Decision support tools (DSTs) are crucial in aiding agricultural decision-making, particularly in improving soil health by enhancing nutrient management, soil organic matter (SOM) and water retention. Despite the availability of numerous DSTs in Europe, their adoption, effectiveness and development needs are not well understood, as most research is based on literature reviews rather than direct feedback from stakeholders. This study aims at filling this gap by conducting an expert survey of the most widely used digital DSTs across Europe on SOM, water retention and nutrient use efficiency in agriculture. We aimed at evaluating the current use, limitations and development needs of DSTs and offering recommendations to improve the effectiveness and adoption of DSTs in the context of soil health. A questionnaire was distributed to experts in 24 countries. Answers were received from 18 countries, including 14 European Union (EU) nations, Norway, the UK, Switzerland and Turkey. A total of 115 DSTs were identified aligning with our definition of DST, with agronomists, consultants and farmers being the primary users. Adoption of DSTs was rated moderate (score: 3.1/5), with tools featuring user-friendly interfaces and alignment with farmer goals achieving higher adoption rates. DSTs were rated better suited to achieve farm-level goals (score: 4.1/5) than regional (score: 3.6/5) or national objectives (score: 3.5/5). Major barriers to adoption included limited end-user involvement in DST development, which may hinder alignment with practical needs. Considering all the received questionnaires, the most frequently cited areas for improvement were nutrient use efficiency (45%), SOM (24%) and water retention (18%). Respondents emphasised the need for better integration of new farming systems (e.g., organic farming, agroforestry), more detailed process descriptions, integration of multiple processes, inclusion of economic modules and improved user interfaces. This study presents the first comprehensive evaluation of DSTs in Europe, revealing a diverse yet moderately adopted landscape. Increasing user engagement, enhancing technical integration and improving accessibility are essential for promoting a wider use of DSTs to improve soil health. By adopting these recommendations, DSTs can play a key role in achieving the EU's sustainability goals, fostering resilient agricultural systems and addressing environmental challenges such as soil degradation and climate change.

Summary

- Decision support tools (DSTs) are needed to foster soil health, but their availability and use are unclear.
- A survey of DSTs in Europe was performed, and their use, adoption and limitations were evaluated.
- Participatory development, alignment with user goals and ease of use are key for DST adoption.
- Integrated tools are needed to boost DST adoption and effectiveness in fostering soil health.

1 | Introduction

Agriculture in Europe faces mounting pressures from environmental, economic and social dimensions, whilst its critical role in ensuring food security is increasingly recognised (Rac et al. 2024). Key drivers of these challenges include climate change (Mihailescu and Soares 2020), soil degradation, water scarcity, market volatility, global competition, agricultural and environmental policies and the demands of technological innovation (EC 2023a; EEA 2023; Hasler et al. 2022; Pe'er et al. 2020). Agricultural productivity relies heavily on preserving healthy soils and their essential functions—such as biomass production, carbon sequestration, nutrient cycling, water filtration and storage and habitats for biodiversity—whilst carefully managing potential trade-offs between these functions (Paul and Helming 2019). These factors form the context in which farmers must make decisions regarding crop and soil management practices, navigating both immediate production needs and long-term sustainability. The importance of soil health is recognised in European policies (Panagos et al. 2022) of EU soil strategy for 2030 (EC 2021), European Green Deal (EC 2020) and the planned Soil Monitoring and Resilience Directive (EC 2023b). Within the European Joint Programme on Agricultural Soil Management (EJP SOIL) cofund research programme, analysis has been made of the most promising management practices and their level of uptake in research, policy and farmers' practice (Keesstra et al. 2021). Previous stock-takes have focussed on 'soil quality indicators' (Pavlů et al. 2021) and 'indicators for monitoring and reference values' (Faber et al. 2022). Building on these stock-takes this study transitions to explore decision support tools (DSTs) designed for the agricultural sector, which leverage soil indicators and other key data to enhance decision-making and management practices.

DSTs can be characterised in diverse ways, reflecting the wide range of models and systems that can function as DSTs, and they are difficult to confine to a single framework (Sánchez et al. 2020; Mir et al. 2015; Power 2002; Shim et al. 2002; Druzdzel and Flynn 1999; Turban 1995; Finlay 1994). In agriculture, DSTs have been developed to aid day-to-day and long-term decision making, and they can play an important role in improving soil health. They typically cover specific aspects of farming, such as nutrient balance, organic matter turnover, pesticide and herbicide doses and application and water management, and include a diverse range of technologies (e.g., algorithm, remote sensing) and digital implementations (e.g., web portal, apps) (Rossi et al. 2014; Wall et al. 2020; Vitali et al. 2021). Other DSTs include multi-criteria decision models for the main soil functions, such as primary productivity or nutrient cycling (e.g., Debeljak et al. 2019). DSTs can be instrumental to support farmers' decision making, improve resource management, increase productivity, yield and cost efficiency towards more sustainable and remunerative farming systems designs. The adoption and effectiveness of DSTs could, however, depend on multiple factors, including understanding of the farmers decision making process (Bartkowski and Bartke 2018), economic endowments and farmers' literacy.

Although a large number of DSTs have been produced in the last decades, very few studies have evaluated those tools, their use and adoption by end users, particularly within Europe over multiple countries. As an example, approximately 81 DSTs have been developed for water management in agricultural systems over the past 40 years. Of these, nearly half are not publicly available and have only been used by developers. Amongst those that are accessible, studies reporting on case applications are limited and scattered (Mabhaudhi et al. 2023). The existing surveys and reviews indicated that socio-economic and farm-specific characteristics are key factors influencing the adoption of DSTs. These are reviewed in the following paragraphs.

A survey of 149 farmers from 11 European countries examined factors influencing the adoption of DSTs for pesticide management. The study found that adoption is influenced by several factors, including the size of the farm (larger farms tend to adopt DSTs more readily), the type of crops grown (certain crops may require specific tools), the cost of using the DSTs (cost barriers can hinder adoption, especially for smaller farms), the experience of the farmer (farmers with more experience may be more confident in using new tools), the attitude of the farmer (positive or negative perceptions can influence adoption) and the user-friendly design of the DSTs (tools that are easy to use and understand are more likely to be adopted) (Akaka et al. 2024 in open review). The findings highlighted that the promotion of those tools should focus on demonstrating productivity benefits for large-scale farms and addressing cost barriers for smaller ones.

A study on integrated pest management (IPM) examined 32 web-based IPM DSTs and found limitations including regional differences in tool availability, lack of consideration for local agroecological contexts, complexity and difficulty of use, proprietary systems limiting access and inadequate feedback mechanisms between users and developers (Tonle et al. 2024). As a result, a user-centred architecture was proposed for future DST development to address these issues and foster DST adoption by end-users.

A review on DSTs aimed at reducing nitrate and pesticide pollution across the European Union (EU) identified 150 tools and further investigated 12 DSTs through practical testing at nine case studies (Nicholson et al. 2020). Factors limiting DSTs acceptability included free availability and open-source design, flexibility in data input/output and transparency in calculations, validation and continuous updates, trust, visualisation of economic benefits and integration with national and European regulations.

An examination of the adoption of 13 DSTs for irrigated cropping systems differentiated between the adoption of DST tools and DST heuristics, noting that discontinuation of DST use may indicate either dissatisfaction or internalisation of the DST heuristics (Ara et al. 2021). The study found that factors such as performance, ease of use, peer recommendation, cost and user-farmer compatibility play a crucial role in the adoption process. A key limitation, however, was the misalignment between DST features and end-user aspirations. Similar suggestions were indicated by Gallardo et al. (2020) who reviewed DSTs for irrigation and nutrient management in commercial vegetable production. The authors found that although the sophistication of DSTs has rapidly evolved, adoption remains low due to tool complexity, large manual data entry requirements and insufficient training and technical support.

A literature review and analysis of eight greenhouse gas (GHG) calculators for horticulture farming in Europe found that these calculators varied in their goals and approaches for estimating GHGs, despite being based on IPCC guidelines (Dzalbs et al. 2023). The study highlighted the importance of user-friendliness, public availability and comprehensive farm-level calculations for greater adoption and effectiveness.

Other studies explored the need for validation and improved integration with policy frameworks of agricultural DSTs. For example, a review of national applications of DSTs for phosphorus (P) management in various countries found that future DST development must prioritise validation against high-quality data, include socio-economic considerations in tool adoption and leverage big data for more accurate phosphorus management (Drohan et al. 2019).

A review of farm models for policy impact assessment in the EU noted scientific progress in model development, but it highlighted persistent limitations in developing consistent evaluation procedures, modularity and transferability (Reidsma et al. 2018). It also pointed out that these DSTs are rarely used in policy impact assessments, in part due to insufficient interaction between scientists and stakeholders during model development. It calls for a stronger focus on farmer decision-making and social factors, as well as improved data collection and stakeholder engagement.

Overall, the above studies emphasise that the adoption and effective use of DSTs are influenced by multiple factors. User-friendliness is a one of the key factors, but DSTs must also be scientifically grounded, transparent and validated (Akaka et al. 2024 in open review; Tonle et al. 2024; Ara et al. 2021; Gallardo et al. 2020; Dzalbs et al. 2023; Nicholson et al. 2020; Drohan et al. 2019). Additionally, the tools must be technologically flexible to support different data inputs and align with diverse user needs and agroecological contexts (Akaka et al. 2024 in open review; Tonle et al. 2024; Dzalbs et al. 2023; Ara et al. 2021; Nicholson et al. 2020; Gallardo et al. 2020; Drohan et al. 2019; Reidsma et al. 2018). Frequently cited barriers to DST use include limited access, high costs and users' attitudes and experiences (Akaka et al. 2024 in open review; Tonle et al. 2024; Dzalbs et al. 2023; Nicholson et al. 2020; Ara et al. 2021). User engagement, for example through feedback and training, in turn positively influences tool adoption and development (Tonle et al. 2024; Nicholson et al. 2020; Gallardo et al. 2020; Reidsma et al. 2018).

The current understanding of DST use, adoption and development needs in Europe is mostly based on existing literature rather than on direct surveys involving end-users, experts or other stakeholders. Systematic stock-takes of the most used DSTs, particularly those that include evaluations by end-users and experts, are notably scarce. This study aims to contribute to addressing this gap by performing a comprehensive stock-take and expert survey of the most used digital DSTs across Europe with a specific focus on three key themes: nutrient use efficiency, soil organic matter (SOM) and water retention. The three themes represent key aspects of soil functions and agricultural production, with their selection guided by the European Joint Programme on Agricultural Soil Management (EJP SOIL 2025). The digital DSTs were defined in this study as follows:

> Digital DSTs are tools that farmers, advisors or policymakers can use to make decisions addressing SOM, water retention or nutrient efficiency. Tools can be software, apps, web portals or on other digital supports. The tool would typically require some data about the soil, crop, field history and weather and then use an evidence-based algorithm to calculate an output. The output could be an analysis of the effect of current or improved soil, water, and nutrient management practices at different scales (e.g., field, farm, regional, national).

The main objectives were to (a) assess the current use, limitations and development needs of digital agricultural DSTs across Europe, with a specific focus on the three key themes (nutrient use efficiency, SOM and water retention), and to (b) provide recommendations to improve the effectiveness and adoption of these tools within the broader framework of fostering soil health. The stock-take and expert survey, was distributed to the National Coordinators (NC) of the EJP SOIL across 24 partner countries, including Turkey. This approach aimed to capture a diverse range of agricultural contexts to provide new insights into the current state and potential development of DSTs in Europe.

2 | Materials and Methods

2.1 | Questionnaire Design and Structure

The questionnaire was developed through an interactive process of design, feedback and improvement within the project teams. The goal of the questionnaire was to gather quantitative and qualitative information on the most common DSTs used in each country participating in the study and to identify critical points and opportunities for future improvements for the DSTs related to SOM, soil water retention and nutrient use efficiency. The questionnaire also examined the current use of different DSTs based on specific farm management practices (e.g., organic vs. conventional), problems encountered, adaptation experiences

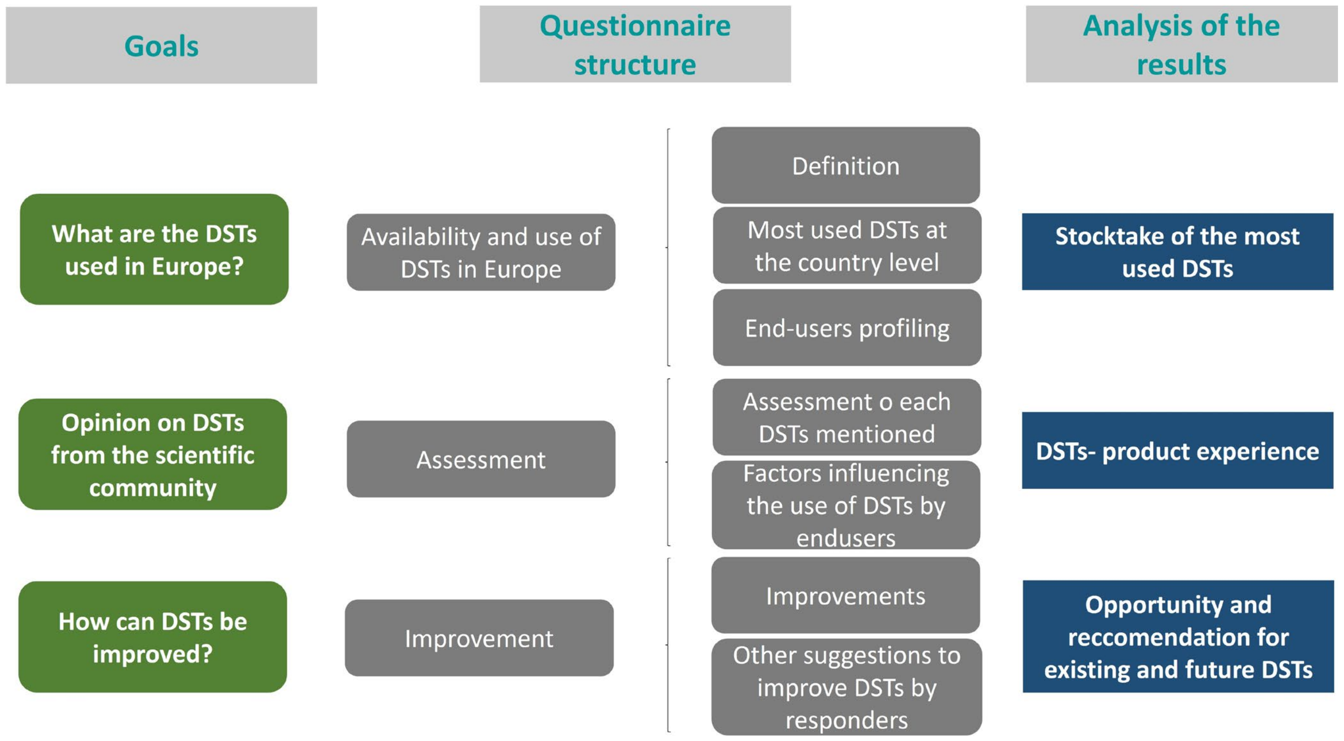

FIGURE 1 | Goals, structure and analysis of the questionnaire sent to the EJP SOIL national coordinators concerning decision support tools related to soil organic matter, soil water retention and nutrient use efficiency in agriculture.

and future development needs. Figure 1 shows the goals, questionnaire structure and analysis of the data collected.

The questionnaire consisted of 16 questions under the following eight themes:

1. Respondent details collected information on the countries, institutions and names of the people who answered the questionnaire.
2. Definition of DSTs and decision-making process facilitated by DSTs asked whether respondents agreed with our definition of digital DSTs, and for what kind of decision-making processes DSTs can facilitate.
3. Current use of DSTs aimed to survey the most used DSTs and asked respondents to list those DSTs in their respective countries.
4. Users of DSTs surveyed the main user groups of DSTs reported by the respondents.
5. Assessment of the reported DSTs requested the respondents to evaluate the reported DSTs against predefined questions related to the use of DSTs, such as adoption by users, user-friendliness, user trust in DSTs, etc.
6. Improvement of DSTs collected the respondent's views on the improvement needs in the reported DSTs, as well as on what kind of DSTs are not available but are needed.
7. Factors determining the use of DSTs investigated respondents' experiences and opinions on the factors that influence the adoption and use of DSTs.
8. Other important aspects not addressed by the questionnaire provided an opportunity for respondents to provide additional views on the use and improvement of DSTs beyond the more structured questions of the survey.

The 16 questions are shown in Table S1. The questions were mainly qualitative, except for one that asked for quantitative information on the use of DSTs. Of the qualitative questions, 11 were open-ended questions and 4 were closed questions with the option to provide additional open-ended information.

2.2 | Questionnaire Dispatch

The questionnaire was sent as a spreadsheet file through email to 26 NCs of 24 countries participating in the EJP SOIL in Europe, including Turkey. The NCs were affiliated with research institutes, universities and government agencies. NCs were recommended to mobilise their network scientists and experts to gather representative data on the use and assessment of DSTs in their respective countries. Two months were given to the NCs to fill in and return the questionnaire responses through email. A help desk was established to assist the NCs, and two online webinars were conducted to provide support for completing the questionnaire.

2.3 | Analysis of Questionnaire Responses

The questionnaire responses from the NCs were first merged and analysed for each individual question. Questions with quantitative information were analysed using descriptive statistics. Pearson's correlations were used to investigate potential relationships in the assessment ratings given for individual DSTs. Questions with qualitative information were analysed through thematic and interpretive analysis by multiple researchers, who identified recurring themes and patterns in the responses. The thematic analysis also involved grouping answers according to the specific themes—SOM, water retention and nutrient use efficiency. Based on this analysis, summary texts and tables of responses were produced for each question, and they are presented here. The detailed answers are presented in the (Tables S2–S12).

2.4 | Artificial Intelligence

The artificial intelligence (AI) tool ChatGPT-4o from OpenAI (https://openai.com/) was used as a supplementary tool to support the discussion of the results in Section 4. The AI capacity to handle complex and diversified data helped to categorise the results and their discussion based on certain criteria defined by the authors. This was used to draft recommendations for enhancing DST adoption and effectiveness. In this process, the section on survey results and their primary discussion (Section 3), written by the authors, was provided as input for the AI, along with the prompt: "Based on the provided survey findings, formulate recommendations for enhancing the adoption, effectiveness and further development of agricultural DSTs for improving soil health across Europe". The initial recommendations generated by the AI were then carefully reviewed and revised by the authors to align with the findings and the authors' views. The resulting recommendations were further re-organised and grouped under specific themes by the authors. This approach provided practical support in synthesising and structuring the discussion but did not constitute a formal part of the research methodology, nor did it influence the results and their primary discussion.

The same AI tool was also used for proofreading the original texts written by the authors. Proofreading involved correcting grammar and syntax and improving fluency. AI was not used elsewhere or otherwise, as stated here.

3 | Results and Discussion

3.1 | Questionnaire Responses and Their Evaluation

3.1.1 | Respondent Details

Responses to the questionnaire were received from 18 countries, including 14 EU countries, Norway, the United Kingdom, Switzerland and Turkey (Figure 2 and Table S2). Two responses were received from Belgium, representing the regions of Flanders and Wallonia. The response rate of the survey accounted for 75% of the EJP SOIL countries. The responses covered 52% of EU member states and 39% of European countries. Those countries represent a range of agricultural conditions in Europe, from Mediterranean to boreal climate, with varying intensity of agricultural practices, technological adoption and economic importance of agriculture.

3.1.2 | Definition of DSTs and Decision-Making Process Facilitated by DSTs

The respondents generally agreed with the given definition of digital DSTs (Section 2.1). Respondents from Finland and Norway, however, suggested other types of digital DSTs that do not strictly fall under the definition provided in the questionnaire. Therefore, the definition used in this study may exclude some tools currently in use.

In the *soil water availability and retention* category, 41 DSTs were reported, of which 31 aligned with the definition; in the *SOM* category, 50 DSTs were reported, of which 37 aligned with the definition; and in the *soil nutrient use efficiency* category, 75 DSTs were reported, of which 64 aligned with the definition. Some tools were often reported in two or more categories. The DSTs that did not align with the survey definition of DSTs were typically maps with static information, web pages or portals with static information, guideline documents, soil sampling and analytical services, etc. Interestingly, agricultural advisors were also reported as DSTs, highlighting their role in farm decision making. The resulting stock-take includes altogether 115 individual DSTs aligning with the definition of this study, and they are shown in Table 1. The reported DSTs are presented in more detail in Tables S5–S7. The classification of whether a DST aligns with the study definition may also include some subjectivity, as the reported tools varied considerably by type, technology and purpose.

All respondents (100%) indicated that DSTs (for the specified topics) can be used to facilitate decision-making related to farm management (Figure 3, Table S3). Almost all respondents (94%) considered that DSTs can aid advisory decision type, more than half suggested (56%) that they can facilitate the type of decisions needed at regional scale, and 63% indicated that DSTs can assist with policy decisions. The respondents recognised also field and national types of decisions that were not recognised in the questionnaire.

At farm scale, DSTs can facilitate decisions related to soil management, yield improvement, farm management, economic profitability, nutrient use, fertilisation schedules, fertilisation limits, soil compaction risk, field mapping, water management, irrigation scheduling, estimation of soil properties, SOM preservation and build-up and reduction of soil erosion (Table S4). Concerning types of decisions relevant for advisors, DSTs can support similar decisions as at the farm scale, highlighting the capacity of DSTs to help advisors validate, objectify and provide more reliable advice to farmers. DSTs can also facilitate decisions needed at regional scale, including applications of nutrient inputs, water management and SOM, as well as economic and environmental assessments (Table S4). DSTs were seen as a valid tool to collect and synthesise important information to develop agricultural policies and regulations that align with societal expectations. At the policy level, DSTs were reported to support the development of agricultural policies, regulations and environmental guidelines and support measures (Table S4). Respondents also indicated that similar decisions as those relevant for farmers and advisors—such as nutrient inputs, water management, SOM and economic considerations—are also relevant for the policy domain, suggesting that this information is valuable across multiple decision-making tiers.

Altogether, DSTs were seen as capable of facilitating different types of decision-making processes. Farmers and advisors' types of decisions relate to more practical, immediate management

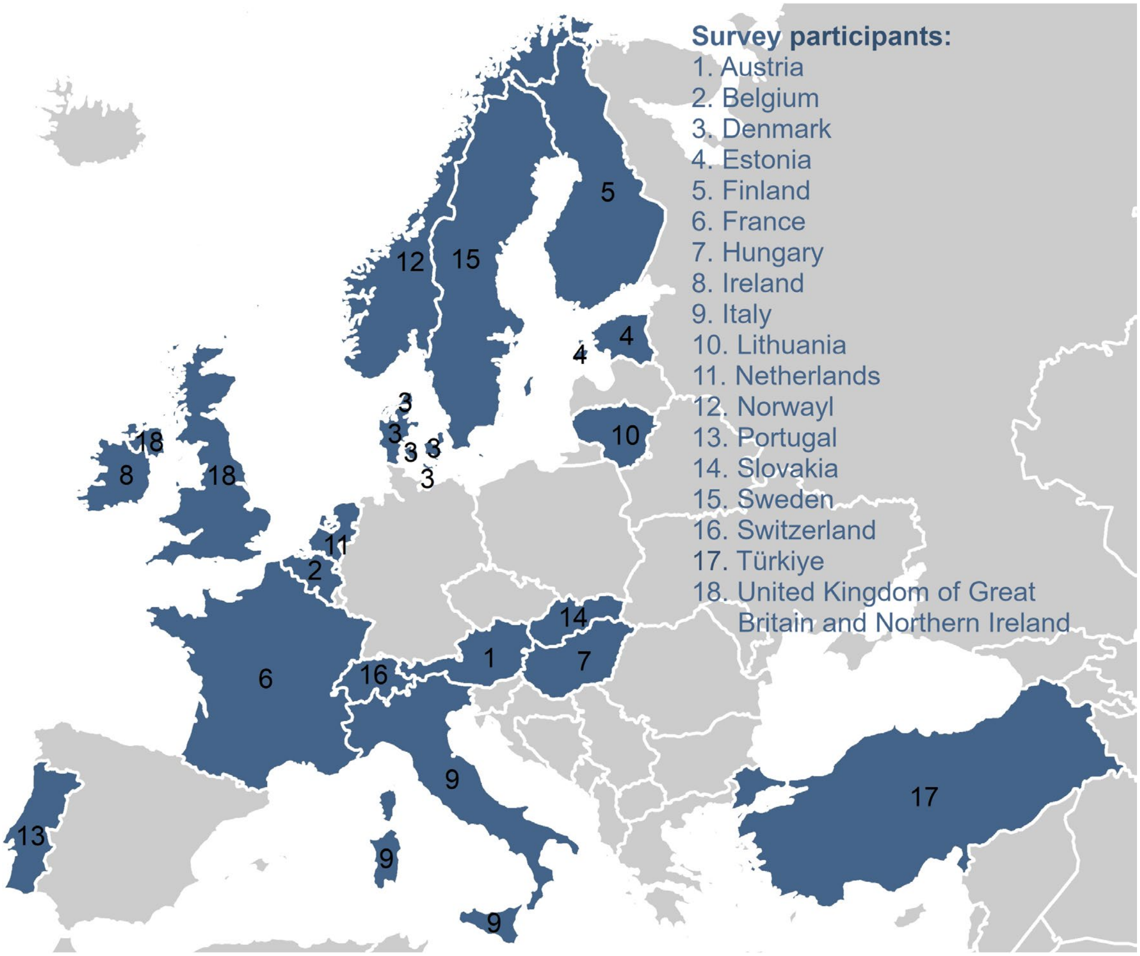

FIGURE 2 | Participant countries of the survey on decision support tools (DSTs).

decisions, whereas at the regional and policy scales, the emphasis shifts towards broader planning and policy-making that considers economic, environmental and societal factors.

3.1.3 | Current Use of DSTs

The resulting stock-take of 115 tools is a representative sample of commonly used DSTs on soil water, SOM and nutrient management across Europe. Interestingly, the same DSTs were rarely reported by two countries, except for (i) AquaCrop (Salman et al. 2021), which was reported by Belgium and Turkey, and (Atfarm 2023) in Norway and Sweden. As a result, we did not notice any regional trends, thereby suggesting that DSTs still have a national rather than a regional relevance.

The DSTs varied widely in purpose (single-purpose, multi-purpose), complexity and implementation (online, offline, mobile applications or tools with hardware components). They also encompass a range of tool types, including activity planners, simple calculators, monitoring-based tools, remote sensing-based tools and models. As a result, clear categorisation of individual tools was challenging.

The reported DSTs in the soil water availability and retention category generally focus on optimising water management in agricultural practices. These include tools for irrigation scheduling, soil moisture monitoring and estimating water requirements (e.g., AquaCrop and soil moisture sensors). The DSTs in the SOM category are typically designed to help farmers and advisors manage SOM or soil organic carbon (SOC). They include calculators for carbon balance, models for SOC turnover and applications for monitoring and predicting changes in SOC stocks (e.g., Cool Farm Tool, Roth C). The DSTs in the nutrient use efficiency category, in turn, are primarily focussed on optimising fertiliser use and managing nutrient inputs to maximise crop yield. These include nutrient calculators, decision aids for fertiliser application and systems for monitoring soil nutrient levels (e.g., NPK balance calculators, PLANET and MANNER-NPK). Some tools for nutrient use efficiency integrate data on soil tests, crop types and environmental conditions to provide tailored recommendations.

The web search for more information on these tools revealed that the available information varied and was often limited. Whilst some tools had dedicated websites and were well documented in scientific literature, detailed information about their functionalities was often scarce. Moreover, technical or scientific description of the tools' mechanisms was either difficult to find or absent from our search results. This may highlight several issues. For example, the development and marketing of DSTs may not be well organised and implemented, information

TABLE 1 | Reported DSTs on soil water retention, soil organic matter and nutrient use efficiency aligning with the DST definition of this study (Section 1).

Country	Decision support tool (DST)
Soil water retention	
Austria	eo4water
Belgium	AquaCrop, SWAP-WOFOST, Waterradar
Denmark	Vandregnskab Online
Finland	Soil scout sensor, field observatory, EU MARS crop monitoring
France	MAELIA
Italy	vite.net, granoduro.net, Elaisian
Netherlands	FarmSoilWaterPlan (bedrijfsbodemwaterplan), irrigation advice, Trijntje
Norway	Calculating water balance, agdir freeland sensor
Portugal	IrrigaSys, irristrat, MOGRA, calendário de rega (Irrigation calendar)
Sweden	Vattennivå i brunn (Water level in wells), raindancer, soil moisture sensor, P–T soil station service, Hur mår min jord? (How is my soil doing?)
Turkey	TAGEM-SuET, TAGEM Soil Fertiliser and Water Resources Central Research Institute National Soil Information System, AgroCares Digital Soil Analysis Device, Filiz& Filizpro, AquaCrop
Soil organic matter	
Austria	Austrian Carbon Calculator
Belgium	Demeter tool, C-slim, CARAT, DECIDE, Cool Farm Tool, CAP'2ER
Denmark	ESGreenTool Climate
Estonia	Humus balance calculator (Huumusbilansi kalkulaator), RothC model, Yasso model
Finland	Pro Agria-WISU, Agrineuvos, Crop rotation comparison tool (Viljelykiertolaskuri)
France	SIMEOS AMG, ABC'Terre, MAELIA

(Continues)

TABLE 1 | (Continued)

Country	Decision support tool (DST)
Ireland	Carbon Navigator, AgNav
Italy	vite.net, granoduro.net, Elaisian
Netherlands	Soil C Tool, Carbon calculator, Veris Soilscan
Norway	Jordplan, Skifteplan
Portugal	VirtuaCrop, Fertile
Sweden	Hur mår min jord? (How is my soil doing?), Odlingsperpektiv (Cultivation perspective)
Switzerland	Humus balance calculator (Humusbilan-Rechner)
Turkey	TAGEM Soil Fertiliser and Water Resources Central Research Institute National Soil Information System
United Kingdom	PLANET, MANNER-NPK, Farm Crap App Pro, MuddyBoots
Nutrient use efficiency	
Austria	ÖDüPlan Plus, Terrazo
Belgium	NEMO, REQUAFERTI, FaST, BELCAM, DECIDE
Denmark	CropManager, MarkOnline
Estonia	NPK balance calculator, fertilizer requirement maps, lime requirement maps, EstModel
Finland	Phosphorus planning tool, nitrogen balance calculator, Pro Agria-WISU, PeltotukiPro, Agrineuvos, nutrient calculator, biomassa-atlas (Biomass Atlas)
France	Syst-N, Azofert, MAELIA
Hungary	PROPLANTA
Ireland	NMP On-line, Pasturebase Irl
Italy	vite.net, granoduro.net, Elaisian
Lithuania	Digital N-fertilisation with sensors (agriPORT), apply nitrogen fertiliser in various proportions, Geoface
Netherlands	NDICEA, VRA Top-Dress N, Dutch Fertiliser Recommendation Advice
Norway	Skifteplan (Agromatic), Jordplan, Klimakalkulatoren, Atfarm, Cropplan, Pix4dFields, Biodrone

(Continues)

TABLE 1 | (Continued)

Country	Decision support tool (DST)
Portugal	OneSoil, Fertil, WiseCrop
Slovakia	ÚKSÚP
Slovakia	Harmonised Registration and Information System (HRIS)
Slovakia	Partial soil monitoring system, SAŽP
Slovakia	Fertilisation schedule, Animal storage capacities
Sweden	Atfarm, Yara N-sensor, CropSat, Winter oilseed rape nitrogen estimator (Kvävevågen), Fertiliser calculator (Gödselkalkylen), Vera, Växtnäringsbalans på nätet, Yara Växtnäringsberäkning (Yara palnt nutrient calculator), Yara Checkit
Turkey	TAGEM Soil Fertiliser and Water Resources Central Research Institute National Soil Information System

Note: More detailed list of DSTs is given in Tables S5–S7.

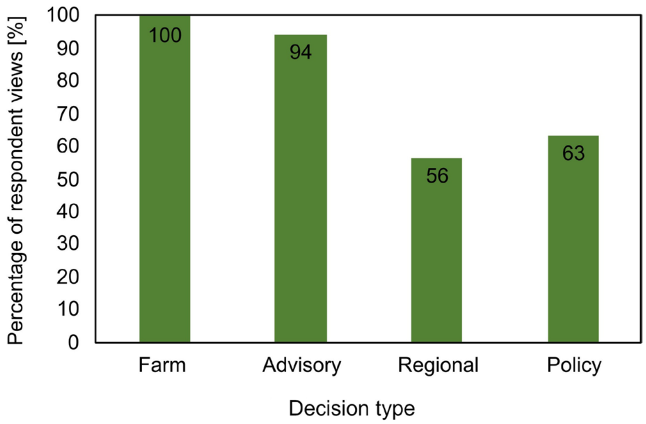

FIGURE 3 | Percentages of respondents' views on which current decision-making levels DSTs (farm, advisory, regional and policy type of decision) can be used.

on tools might be available only in local languages, making the information difficult to find, and the DST may be developed by private companies that may not have incentives to share publicly detailed descriptions of the tools. This limited availability of information, however, suggests a need for improved information on available tools. The lack of comprehensive information can significantly hinder their adoption and evaluation.

3.1.4 | Users of DSTs

The largest users' group of reported DSTs (Table 1) were agronomists, consultants and advisors (80%), followed by farmers (78%), researchers (51%), private companies and NGOs (27%) and policymakers responsible for monitoring (23%) (Figure 4 and Table S8). One respondent also noted that education was a user group, whilst another highlighted a distinction between two types of users: those who interact with the models directly and those who only utilise the model outputs.

There is also overlap in the use of the same DSTs across different user groups, though with some variation (Table 2). The largest overlap in tool use was between farmers, agronomists, consultants and advisors and researcher user groups. Farmers used 71 tools, of which 57 were used by agronomists, consultants and advisors, and 36 by researchers. Agronomists, consultants and advisors, in turn, used 73 tools, of which 41 were used by researchers. The lowest overlap in the use of the same DSTs was generally between monitoring policy makers and other user groups. These findings indicate that some DSTs serve multiple groups, whilst others are better suited to specific user groups.

3.1.5 | Assessment of the Reported DSTs

According to respondents' ratings of DSTs on a scale of 1–5, the adoption of DSTs by end users seems modest, with an average rating of 3.1 (Tables 3 and S9). In terms of suitability for reaching goals, DSTs were considered well suited for achieving farmer goals, with an average rating of 4.1. They were deemed slightly less suitable for reaching regional and national goals, with average ratings of 3.6 and 3.5, respectively. The DSTs were perceived to have limited participation of end users or co-innovation processes in their development, with an average rating of 3.3. Data input requirements were considered modest, averaging 2.7, and most respondents found the interfaces user friendly, with an average rating of 3.7. The cost of using DSTs was found to be low, with an average rating of 1.8. Notably, DSTs were largely perceived as reliable, with an average rating of 3.9.

The DSTs with the highest adoption rate (rating = 5) were found to have more user-friendly interfaces (average rating +0.8) and were considered more suitable for reaching farmer, regional and national goals (+0.5 to +1.0) when compared to average ratings of all DSTs (Table 3). Their costs were also somewhat lower (−0.3), but their data input requirements were considered higher (+0.5) compared to all DSTs.

The correlation analysis of the rating scores given for individual DSTs mostly provided low and modest statistically significant correlations between the 10 assessment questions ($p < 0.01$) (Table 4). The highest statistically significant correlations were observed between the suitability of DSTs for farmers, national and regional goals. The DSTs that were suitable for regional goals appeared to be appropriate also for national goals ($r = 0.82$). Also, some DSTs that are suitable for reaching farmer goals appeared to be suitable also for regional and national goals ($r = 0.52$ and 0.38, respectively). The correlation analysis further showed that the adoption by end-users depends on the suitability to reach the goals at the three levels ($r = 0.4$–0.52) and on a user-friendly interface ($r = 0.41$). Surprisingly, the adoption by end-users did not seem to have a clear relationship with data input, perceived reliability, cost, or participatory development

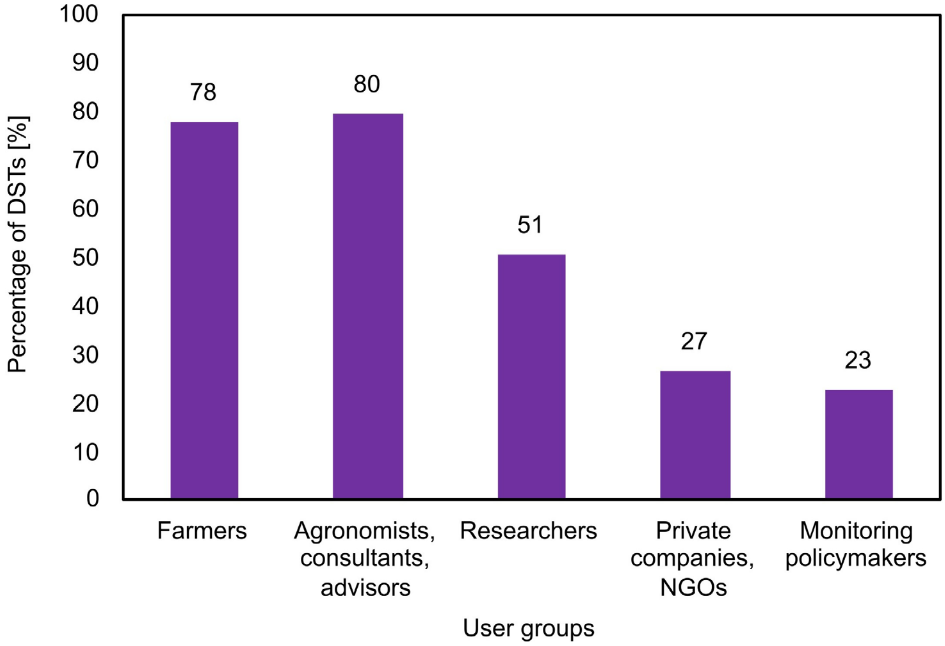

FIGURE 4 | Percentage of the reported DSTs used by user groups.

TABLE 2 | Matrix on the number of the reported DSTs with overlapping use across user groups.

	Farmers	Researchers	Agronomists, consultants and advisors	Private companies and NGOs	Monitoring policy makers
Farmers	**71.**	36	57	17	11
Researchers	—	**46**	41	18	19
Agronomists, consultants and advisors	—	—	**73**	22	18
Private companies and NGOs	—	—	—	**25**	11
Monitoring policy makers	—	—	—	—	**21**

Note: The total number of DSTs in the analysis was 91, and the number of DSTs used per user group is shown on the diagonal of the table in bold. For example, 71 tools were reported to be used by farmers, of which 36 tools were also used by researchers and 57 by agronomists, consultants and advisors.

with non-statistically significant correlations between −0.12 and 0.13. However, a statistically significant correlation was found between the perceived reliability and suitability to reach farmers and regional goals ($r=0.42$ and 0.35, respectively).

Altogether, the assessment of DSTs highlighted a nuanced perspective on their adoption and effectiveness across different levels of agricultural decision-making. It suggested potential barriers to the widespread utilisation of DSTs, whilst they were perceived as suitable for achieving farmer-specific goals with diminishing suitability at broader regional and national scales. A notable observation was the limited engagement of end-users in the development of these tools. This lack of user involvement may contribute to the challenges in aligning DSTs with goals at different levels. Despite this, DSTs were generally perceived as reliable and user-friendly, but they may not always fully meet the needs of end-users.

Interestingly, DSTs with the highest adoption rates (adoption by end-users = 5; Table 3) were associated with more user-friendly interfaces and were perceived as more effective in achieving goals at all levels—farmer, regional and national. This indicates that ease of use and clear alignment with user goals are critical factors driving adoption. However, the higher data input requirements for these highly adopted tools suggest a trade-off between the complexity of data needed and the value derived from using these DSTs.

According to results obtained from the correlation analysis (Table 4), the adoption of DSTs was significantly influenced by the users' perceived suitability to meet various goals and the user-friendliness of the DST interfaces. The strong correlations between the suitability of DSTs for farmer, regional and national goals indicated that many DSTs can potentially serve multiple decision-making tiers. However, there was a marked differentiation, particularly in tools aimed at farmer goals, which may not fully align with the broader objectives at national levels. Other factors such as data input requirements, perceived reliability and participatory development processes showed weaker correlations.

TABLE 3 | Average ratings for the assessment of DSTs (decision support tools) by respondents.

Question	Rating	All DSTs Average score	All DSTs Standard deviation	All DSTs *n*	DSTs with the highest adoption rate Average score	DSTs with the highest adoption rate Standard deviation	DSTs with the highest adoption rate *n*
A. Adoption by end-users	1 = little or no use 5 = widely adopted	3.1	1.3	81	5	0	14
B. Is the use of the tool optional?	1 = Yes 2 = No	1.1	0.4	87	1.3	1.1	14
C. Data input	1 = few data needed 5 = many data needed	2.7	1.2	82	3.1	1.3	14
D. User-friendly interface	1 = too complex for users 5 = very user friendly	3.7	1.0	83	4.4	0.8	14
E. Perceived reliability of the DST	1 = low reliability 5 = very high reliability	3.8	0.8	80	4.1	0.9	14
F. Cost of the DST	1 = free of charge 5 = very expensive	1.8	1.2	82	1.5	0.9	14
G. The tool has been developed with participatory research/co-innovation	1 = no users involvement in the design 5 = user-centred design	3.3	1.3	74	3.2	1.6	13
H. Suitable to reach national goals	1 = not suitable 5 = very suitable	3.5	1.4	80	4.4	1.3	13
I. Suitable to reach regional goals	1 = not suitable 5 = very suitable	3.6	1.4	79	4.6	0.9	14
J. Suitable to reach farmers goals	1 = not suitable 5 = very suitable	4.1	1.0	89	4.6	0.6	14

Note: The total number of DSTs analysed ranged from 74 to 89 per question. DSTs with the highest adoption rates are those receiving a score of 5/5, indicating wide adoption by end-users.

3.1.6 | Factors Determining the Use of DSTs

The majority of respondents (68%) identified farmers' education as a key driver for the adoption of DSTs by end-users (Table 5). In comparison, farmer participation in associations or cooperatives was considered a less significant factor, with only 50% of responses falling between 'strongly agree' and 'somewhat agree.' Additionally, respondents indicated that crop farmers are more inclined to use DSTs than livestock farmers, though a quarter of the respondents reported limited knowledge on this topic.

Approximately 40% of respondents indicated unfamiliarity with activities conducted in Living Labs related to DSTs. The data concerning digital illiteracy were inconclusive, preventing strong conclusions from being drawn. Finally, respondents suggested that the use of DSTs is not influenced by specific management approaches such as biodynamic or organic farming.

Altogether, the responses underscore the pivotal role of farmer education in the adoption of DSTs. The discernible preference for DST use amongst crop farmers compared to livestock farmers may reflect the specific utility of DSTs in crop management, where precise decision-making on inputs and scheduling can directly influence yield and profitability. However, the limited knowledge reported by a quarter of respondents about DST use in livestock farming suggests an area for further exploration and education. It is also likely that the backgrounds of the respondents were more in plant cultivation and soils than in animal husbandry. The responses also highlight a gap in awareness regarding the role of Living Labs in promoting DSTs. This indicates a potential disconnection between innovation hubs and the broader farming community, suggesting a need for better communication and outreach.

3.1.7 | Improvement of DSTs

The respondents provided a range of feedback on how the reported DSTs could be improved for nutrient use efficiency, SOM and soil water availability and retention. Responses showed that 45% of DSTs that can be improved concerned soil nutrient use efficiency, whilst 24% regarded SOM, 18% focussed on soil water availability and retention and only 10% of DSTs that can be improved were integrated.

The improvement needs for individual DSTs were often very detailed (Table S10). On a more general level, the improvement needs concerned the integration of new farming systems'

TABLE 4 | Results of the correlation analysis of assessment ratings given to individual DSTs in the 10 assessment questions by the respondents.

	A. Adoption by end-users	B. Is the use of the tool optional?	C. Data input	D. User friendly interface	E. Perceived reliability of the DST	F. Cost of the DST	G. The tool has been developed with participatory research/co-innovation	H. Suitable to reach national goals	I. Suitable to reach regional goals	J. Suitable to reach farmer goals
A. Adoption by end-users	—	0.18 (0.1624)	−0.02 (0.8482)	**0.41 (0.0007)**	0.2 (0.118)	−0.12 (0.3352)	0.13 (0.3232)	**0.43 (0.0004)**	**0.52 (< 0.0001)**	**0.4 (0.0010)**
B. Is the use of the tool optional?	—	—	**0.27 (0.0314)**	0.2 (0.1198)	−0.13 (0.3057)	−0.11 (0.4036)	−0.07 (0.5732)	0.07 (0.5718)	0.16 (0.2137)	0.12 (0.3513)
C. Data input	—	—	—	**−0.23 (0.0640)**	−0.12 (0.3477)	0.17 (0.1907)	0.01 (0.9586)	−0.03 (0.8063)	−0.1 (0.4173)	−0.03 (0.8442)
D. User-friendly interface	—	—	—	—	**0.28 (0.0255)**	−0.18 (0.1558)	**0.31 (0.0120)**	**0.25 (0.0433)**	**0.4 (0.001)**	**0.5 (< 0.0001)**
E. Perceived reliability of the DST	—	—	—	—	—	0.12 (0.3447)	**0.25 (0.0470)**	**0.29 (0.0208)**	**0.35 (0.0041)**	**0.42 (0.0005)**
F. Cost of the DST	—	—	—	—	—	—	0.15 (0.2438)	−0.04 (0.7241)	−0.14 (0.2531)	−0.05 (0.7022)
G. The tool has been developed with participatory research/co-innovation	—	—	—	—	—	—	—	0.11 (0.3769)	0.19 (0.1352)	0.09 (0.4703)
H. Suitable to reach national goals	—	—	—	—	—	—	—	—	**0.82 (< 0.0001)**	**0.38 (0.0017)**
I. Suitable to reach regional goals	—	—	—	—	—	—	—	—	—	**0.52 (< 0.0001)**
J. Suitable to reach farmers goals	—	—	—	—	—	—	—	—	—	—

Note: p values are given in brackets ($n = 64$), and statistically significant correlations are in bold ($p < 0.1$).

TABLE 5 | The respondents' views on factors determining the use of DSTs.

Factor	Strongly agree (%)	Somewhat agree (%)	Neither agree or disagree (%)	Somewhat disagree (%)	Strongly disagree (%)	I don't know (%)
A. Farmer education is a critical factor in determining the use of DSTs by farmers	32	36	14	14	0	5
B. Members of farmers' associations and cooperatives tend to use DSTs more than individual farmers	10	40	30	5	5	10
C. Crop farmers tend to use DSTs more than livestock farmers	10	40	20	5	0	25
D. DSTs are used by Living Labs	21	11	26	5	0	37
E. Digital illiteracy is amongst the main factors hampering the use of DSTs	14	29	19	19	14	5
F. Organic and biodynamic farmers tend to use DSTs more than conventional farmers	0	17	30	22	9	22

options (e.g., organic farming, agroforestry), more processes (e.g., SOC stocks and sequestration, P and potassium (K) fertilisation), improved methods for calculations and estimations (e.g., process description, suitability for different conditions), better validation against observations in different conditions, improvements in data inputs (e.g., more updated data, more user flexibility, possibility to incorporate various data sources and lower data input requirements) and improvements in user-friendliness (e.g., design, user interface, visualisation and interpretation of results). Other improvement needs included web and mobile applications, an option for scenario calculations, scalability over space and time and suitability to support regulatory compliance.

Altogether, the feedback from respondents on improving reported DSTs highlighted a diverse range of improvement needs, reflecting the varied needs across different aspects of agricultural management. The most pressing needs concerned effective nutrient management solutions, improved integration of new farming systems and the expansion of processes covered by DSTs. The respondents' feedback underscores the necessity for DSTs that are not only technically robust and scientifically validated but also user-centric and adaptable to a wide range of farming practices and conditions.

The responses on what type of tools could be developed provided a range of suggestions for SOM, nutrient use efficiency and water retention (Table S11). The responses suggested that there is a general need for software, applications and web-based tools, as well as for sensors and monitoring tools and remote sensing and forecast tools. In the case of SOM, the respondents suggested DSTs that account for soil health indicators, thresholds for SOM/SOC, carbon credits, regional carbon balances and life cycle analysis. For nutrient use efficiency, DSTs were suggested to account for soil nutrient status, fertilisation balance and overfertilisation. For water retention, DSTs' improvements regarded soil moisture status, water requirements and irrigation need, as well as DSTs able to forecast soil moisture conditions. Also, a DST that provides information on the traffic ability of the fields was suggested. In the case of integrated DSTs, suggestions were made for single-entry web portal instead of multiple individual tools. For example, a suggestion was made for a tool that integrates multiple sustainable goals related to soil functions, such as primary production, water quality, climate change, nutrient cycling and biodiversity.

According to the respondents, the use of these tools can help both farmers' and the regional objectives to be achieved (Table 6). DSTs can help to make informed management decisions, achieve the regional SOC target and develop sustainable climate policies. DSTs could also assist farmers in reducing inputs and increasing farm economic profitability, whilst providing sustainable recommendations for soil management, soil fertility and crop rotation. DSTs could also be instrumental in exploring farm designs able to meet environmental targets, optimise the use of resources and inputs and increase productivity.

The responses indicated a comprehensive range of suggestions for the development of new DSTs. There was a strong call for a variety of technological solutions. Our results highlighted a preference for integrated DSTs, with suggestions for a unified web portal that consolidates multiple sustainable goals, including primary production, water quality, climate change mitigation, nutrient cycling and biodiversity. Such integrated tools were considered pivotal in helping farmers and regional stakeholders achieve their objectives.

TABLE 6 | Farmers' and regional goals that could be reached more easily if the new suggested tools are developed and used.

	Which regional goals could be reached more easily if those tools are used?	Which farmers goals could be reached more easily if those tools are used?
Soil organic matter	• LULUCF targets • Climate policies • Retention of soil carbon, soil C balance • Regional SOC targets • Informed management decisions • Sustaining/improving soil carbon • In terms of soil fertility and soil health, it could contribute to monitor, maintain and increase SOC	• Strategies to gain carbon credit • Reduce inputs and increase the economic profitability of farms • Recommendations for crop rotations • Soil management • Farm-level carbon budget calculation • Increase carbon content • Reduce costs and sustainable production • To make informed management decisions • Sustainable soil management monitoring • Sustaining/improving soil fertility and soil water retention • Increasing and maintaining the productivity of farmer's land, will provide more income, protect soil against climate change
Nutrient use efficiency	• Reduce GHG emission without reducing yield • Reduced nitrate leaching • Nitrates directive • Environmental policies • Water quality maintenance/improvement and GHG mitigation • Less soil package and use of nutrition • Informed management decisions • In terms of soil fertility and soil health, it could contribute to achieve nutrient balance and better nutrient management in soil.	• Fertiliser use efficiency • Reduce inputs and increase the economic profitability of farms • Reduce N & P surplus and risk of loss per hectare. • Reduce fertiliser quantity & costs. • Increased soil fertility due to improved nutrient (incl. manure) distribution within the farm • Better yield, more sustainable farm, historical data • Reduce costs and sustainable production • To make informed management decisions • Increasing and maintaining the productivity of farmer's land, will provide more income, protect soil against climate change.
Water retention	• Demand of water for irrigation • Drought preparedness • Improving soil health and soil functions. Minimising the risk of nutrient runoff due to reduced water infiltration rates • Water saving • Proper irrigation management and early detection of drought	• Reduced use of irrigation water • Irrigation scheduling, yield estimations • Farm specific and cost-effective interventions • Irrigation efficiency • Optimising soil moisture • Increasing and maintaining the productivity of farmer's land, will provide more income, protect soil against climate change.
Integrated tools	• Reducing nutrient losses and carbon footprint of agriculture, etc	• Profit, lower environmental impact (incl. preserving soil health/quality) • All farmers and advisory services

Abbreviations: GHG, greenhouse gas; LULUCF, land use, land-use change and forestry; N, nitrogen; P, phosphorus.

TABLE 7 | Additional aspects that were not mentioned in the questionnaire but could be considered in the use and development of DSTs related to soil water retention, soil organic carbon and nutrient use efficiency.

Theme	Additional aspects
Soil water retention	
Comprehensive data integration	Integrating accurate and comprehensive data on soil characteristics and soil hydrology into DSTs. These data serve as foundational elements for effective decision-making in soil water retention and irrigation management.
Incorporating farming practices	To enhance the practicality and relevance of DSTs, it is recommended to include information on farming practices, such as the use of cover crops and tillage. These practices significantly impact soil water dynamics and should be integral components of the decision-making process.
Pedotransfer functions	The inclusion of pedotransfer functions within DSTs is advised to improve the accuracy of soil hydrological data. Pedotransfer functions enable the estimation of essential hydrological parameters directly within the model, thereby enhancing precision in soil water retention predictions.
Economic module integration	Given the increasing profitability of irrigation in regions like Finland due to climate change, there is a compelling argument for integrating an economic module into DSTs. This module would support farmers in making economically sound decisions regarding irrigation and water management, not limited to Finland.
Co-creation during DST development	Engaging end users during the development stage of DST was flagged as a critical step to ensure (i) relevance of the DST for end users and (ii) actual use of the DST by end user in the decision-making process.
Soil organic matter	
Comprehensive soil testing	NCs emphasised the importance of accurate soil testing that incorporates a broad spectrum of soil parameters. This includes specific considerations for sampling depth. Such comprehensive data are crucial for improving the precision and utility of DSTs in SOM management.
Temporal considerations	Recognising the temporal dimension of SOM stabilisation emerged as a significant recommendation. Soil organic matter processes can span years, and DSTs should account for this extended timeframe to provide realistic and effective results based on different management strategies.
Historical data integration	To enhance the robustness of DSTs, it is advisable to incorporate historical data. Historical information allows for accurate validation and calibration of models, thereby increasing their reliability in predicting SOM dynamics.
Influence on soil health	Respondents recommended integrating the influence of SOM on chemical, physical and biological soil health. This addition can make the benefits of improving SOM more explicit to end users and emphasise the broader positive impacts on soil quality and productivity.
Microorganism modules	An intriguing suggestion is the integration of specific modules related to microorganisms. These modules would offer a more comprehensive view of the processes associated with SOM stabilisation, considering the critical role microorganisms play in SOM dynamics.
Nutrient use efficiency	
Incorporating SOM data	Respondents underscored the significance of incorporating data on soil organic matter into DSTs. This inclusion would enable DSTs to provide estimates of soil nutrient pools and the nutrients available for mineralisation, offering critical information for nutrient management.
Integration of farm management and crop yield data	It is recommended to integrate farm management practices and crop yield data into DSTs. This integration would facilitate the calculation of nutrient use efficiency under varying circumstances, enabling farmers to optimise nutrient utilisation.
Multi-year monitoring	Acknowledging the temporal dynamics of soil processes, respondents advocated for multi-year monitoring within DSTs. Such an approach would enhance tool reliability by accounting for variability across cropping seasons and capturing long-term trends in nutrient management.
Expanded analytical scales	To provide a more holistic perspective, respondents suggested expanding the analytical scales beyond the farm gate. Assessing nutrient efficiency at regional and national levels would offer valuable insights into the environmental performance of specific areas or countries, supporting more informed policy decisions.
Integration of the GHG module	Given the potential negative impact of over N-fertilisation, respondents recommended to include a module able to calculate potential and actual gaseous N losses in DST related to nutrient use efficiency. This would serve to make visible the impact of fertilisation on GHG emission.

3.1.8 | Other Important Aspects

The respondent's identified also other aspects for improving DST concerning soil water retention, SOM and nutrient use efficiency (Tables 7 and S12). They emphasised the importance of engaging end users in the development process to ensure the tools are practical and relevant. For SOM, accurate soil testing, temporal considerations, historical data integration and modules that reflect the role of microorganisms were considered crucial. In nutrient use efficiency, incorporating SOM data, farm management practices, multi-year monitoring and expanding analytical scales were mentioned as essential to optimise nutrient use and assess environmental impacts. Additionally, integrating a GHG module could highlight the environmental consequences of fertilisation practices. These considerations can potentially enhance the precision, applicability and overall effectiveness of DSTs in supporting sustainable agricultural practices.

3.2 | Comparison to Literature

The level of implementation of DSTs and guidelines for sustainable soil management in Europe varies considerably amongst farmers and regions. Limiting factors for adoption include access to the tools and availability of required input data and uncertainty in the reliability of tools given regional conditions (Nicholson et al. 2020). At the national level, DSTs may be available which could be made appropriate for wider use across Europe. Scientific papers allow for the export of underlying principles and approaches, but expertise from the farm practical level is seldom shared outside national boundaries. Several studies have identified a large variety of limiting factors, including differences in advisory frameworks, country-specific data and calibration requirements and issues around language (Hvarregaard Thorsøe et al. 2019; Rose et al. 2017).

Our findings broadly aligned with previous reviews and surveys on DSTs in Europe, strengthening the understanding of the limitations in their use and development needs. Our results agreed with the existing literature (e.g., Gallardo et al. 2020; Ara et al. 2021) and identified the following factors as key for the adoption of DSTs: user-friendliness, lack of end-users' participation in the design phase of DSTs, complexity, cost and compatibility with user needs. We highlighted that tools requiring extensive input and setups from the user are less likely to be adopted by farmers—an observation consistent with earlier studies. Bartkowski and Bartke (2018) also emphasised that the socio-economic context, including farm size, education level and crop types, influences DST adoption. Our findings similarly pointed to farmer education and the local context as critical drivers for DST uptake. Both our results and several studies (e.g., Tonle et al. 2024; Gallardo et al. 2020) call for DSTs that are user-centric in design, emphasising the importance of involving end-users during tool development. We provided new insights into how participatory processes (or the lack thereof) affect the relevance and adoption of DSTs. We found that tools developed without significant user input tend to have lower adoption rates. This expands on earlier calls for participatory development (e.g., Ara et al. 2021) by offering empirical evidence through surveys of soil scientists and experts. For climate-driven DST, co-production has also been reported as a success factor for adaptation by farmers (Lu et al. 2022).

Similar to the findings by Nicholson et al. (2020), our results highlighted regional challenges for DST adoption, including differences in agroecological contexts (e.g., climate, soil types, hydrology, cropping systems, etc.). The results showed that the same DSTs are rarely adopted across countries, suggesting a barrier to cross-border knowledge exchange, echoing earlier studies.

3.3 | Limitations and Future Research Directions

To the best of our knowledge, this paper presents a unique stocktake on the availability and use of DSTs on SOM, water and nutrient management in agriculture in Europe. Nevertheless, the following limitations should be acknowledged when considering these data. First, the data collected are expert opinions expressed mainly by researchers from the EJP SOIL consortium and not by end-users, such as farmers. Second, not all the countries contacted provided an answer to the questionnaire. The survey reached the majority (75%) of the EJP SOIL countries, but responses were received from 52% of EU member states. Responses from large agricultural countries, such as Spain, Germany and Poland, were not available. Third, not all the NCs were experts on the three DST types considered and/or mobilised their network to collect representative data at the country level. This may have resulted in variation in the quality of the responses across countries. Also, as ours was not the first stock-take within the EJP SOIL Programme, respondents may have received too many questionnaires, which may reduce the motivation to participate and provide well-considered answers. Furthermore, our focus on DSTs was also based on a broad but limiting definition of digital DSTs. Our interpretation is extended to the broad framework of Soil Health but is based on three aspects only. Research on DSTs for other topics, i.e., soil biodiversity, may add to the knowledge base for developing next generation tools. Finally, correlation analysis should be interpreted with caution, as it does not establish causal relationships amongst the factors under consideration.

4 | Recommendations

Based on the survey findings, recommendations were formulated for enhancing the adoption, effectiveness and further development of DSTs for improving soil health across Europe. These recommendations are shown in Table 8, and they are categorised under four themes: integration and applicability of farming systems, data and knowledge integration, user-centred design and accessibility and trust and compliance.

5 | Conclusions

This study presents the first comprehensive survey on digital DSTs in Europe, focussing on nutrient use efficiency, SOM and water retention, thereby expanding knowledge on their adoption, use and development needs. Our survey of experts revealed

TABLE 8 | Recommendations for enhancing the adoption, effectiveness and development of DSTs.

Theme	Recommendation	Description
Integration and applicability of farming systems	Integration of economic, soil health and environmental considerations	Develop modules that support simultaneous analysis of agro-economic, soil health and environmental outcomes of farming decisions. Integration of operational, tactic and strategic farming decisions can result in appealing tools with more significant management outcomes. The inclusion of dashboard with economic, productive and environmental indicators can support the transition to towards regional soil health e.g., in Living Labs.
	Incorporation of farming practices	Provide flexibility to use the tools for various farming systems (e.g., organic farming, agroforestry) and management practices (e.g., cover cropping, crop rotation and tillage practices). These are crucial for making the DSTs applicable to diverse farming contexts.
	Adaptability across different agroecological conditions	Enable adaptation of the tools to different climatological, soil, agricultural and socio-economic conditions. Provide predefined settings but allow user to adjust the basic assumptions of the tools, including input data, parameterization and calculation methods. This can enhance adoption over wider regions and conditions.
Data and knowledge integration	Build upon latest scientific knowledge and comprehensive data integration	Ensure that the tools are based on latest scientific knowledge, and they cover newly emerging focus areas on soil health to maintain their relevance and capacity to respond emerging challenges in soil health. Allow integration of up-to-date, accurate and comprehensive, input data from a range of available data sources, for example on climatological and hydrological conditions and soil characteristics. Provide also flexibility for user defined data inputs.
	Advanced analytical capabilities	Provide options for historical, real-time, scenario calculations and analyses. Allow scalability of the tool across different scales (field, farm, regional and national).
	Technological versatility	Develop tools that are available on multiple platforms, including web-based, stand-alone and mobile applications. Consider integrating remote sensing and real-time monitoring tools and hardware for enhanced data collection and analysis.
User-centred design and accessibility	Enhanced user involvement in development and in improvement	Engage end-users throughout the development process and collect feedback from users of the tools to ensure relevance practicality and continuous development of DSTs. Living Labs may represent a suitable environment to design DSTs that are able to reflect end-users needs, whilst being scientifically robust.
	Improving user-friendliness	Focus on improving user-friendliness of the DST, for example in the case of user interface, data input process and user support. User-friendliness is one of the key factors influence the tool adoption.
	Enhance information and accessibility	Improve availability of information on available tools, their functionalities and technical foundations in through relevant channels, including web pages, events, trainings and local advisors and farmer cooperatives. Provide the information in relevant languages to promote their wider adoption and use. Introduce use cases to increase the appeal of the tool. Enable low threshold and easy access to tools, whilst considering the user costs and willingness to pay.
	Development of online platform	Build a collaborative online platform that provide access to multiple tools and information covering different aspects and conditions of farming across regions. A collaborative decision support hub can bring together tool users and developers, researchers and policy makers, providing a valuable access and meeting point, thereby enhancing the development of DSTs and adoption of the tools. Include open discussion forum to allow free knowledge and user experience exchange.
Trust and compliance	Foster trust between users and DSTs	Provide information on correctness and accuracy of the tool, for example through use case examples with tool validations. Provide users opportunity to calibrate and validate against their own data and farming conditions.
	Designing tools to align policy and sustainability	Design tools to align with agricultural and environmental policies to support the achievement of overall sustainability goals. Include features that assist users in complying with local and regional recommendations and regulations, such as those related to nutrient management and environmental conservation.

a diverse landscape of DSTs within type (e.g., planning tools, simple calculators, models and monitoring or remote sensing tools), complexity and implementation formats (e.g., software, web tools and mobile applications). These tools were used for different types of decisions (from farm management to policymaking), but they were primarily applied at the farm level, with the largest share of tools focussing on nutrient use efficiency. Despite their potential, the adoption rate was surprisingly modest, and the same DSTs were not widely used across multiple countries. The adoption of tools by end-users was influenced by multiple factors, with the most significant being alignment with end-user goals and user-friendliness.

The reported improvement needs of DSTs covered various aspects, including user-friendliness, specific tool features, reliability and adaptability to different farming systems. End-user engagement through participatory tool development was also found to be crucial in ensuring that DSTs align with end-users' practical needs. These findings also call for integrated and scientifically robust DSTs that are adaptable and capable of accounting for diverse agricultural contexts and data environments.

In the context of soil health, a common limitation of DSTs was their narrow focus on specific processes, often neglecting a broader range of soil functions. Effective DSTs should incorporate soil health, economic and environmental factors, enabling farmers to make informed day-to-day and long-term decisions that support both productivity and long-term sustainability. Based on the survey findings, a set of specific recommendations was developed under four key themes to enhance the adoption and effectiveness of DSTs whilst supporting soil health and agricultural objectives. These four themes include: integration and applicability of farming systems, data and knowledge integration, user-centred design and accessibility and trust and compliance.

From a broader perspective, integrated DSTs aligned with European agricultural and environmental policies can have the potential to advance sustainable agriculture and soil health goals (e.g., EU soil strategy for 2030). Greater development and adoption of these tools can help improve nutrient cycling, enhance carbon sequestration and optimise soil hydraulic properties, amongst other soil functions. This, in turn, would better equip agricultural systems to address key environmental challenges, including soil degradation, climate change and water scarcity. An online platform for sharing and accessing DSTs across different regions and national boundaries was also envisioned as part of the recommendations, fostering further cross-border development and uptake.

Future research on the development of DSTs should focus on integrated tools, incorporation of soil health indicators and a deeper understanding of end-user perspectives to better align DST features with practical needs. Additionally, improving DST accessibility, technological flexibility and policy alignment will be crucial for widespread adoption. By addressing these challenges, DSTs can play an important role in advancing soil health and sustainable agriculture across Europe.

Author Contributions

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that supports the findings of this study are available in the Supporting Information of this article.

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Supporting Information

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