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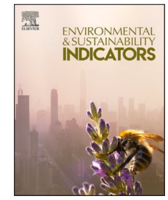

Digital and smart technologies to enhance biodiversity in agricultural landscapes: An analysis of stakeholders' perceptions of opportunities and challenges for broader adoption

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ABSTRACT

Digital and smart technologies (DSTs[1]) for agriculture are currently widely discussed in the literature and increasingly included in common farming practices. However, the main agricultural use of DSTs remains yield-increasing and effort-reducing applications focused on the economic advantages of precision. The potential of DSTs to enhance biodiversity in agricultural landscapes has rarely been examined, especially from the stakeholder perspective. In this study, we examined the barriers to and potential for using DSTs to promote biodiversity in agricultural areas in Germany. For this purpose, we conducted a nationwide stakeholder acceptance analysis based on an online survey and an expert discussion. Our analysis revealed the notable potential of DSTs to strengthen biodiversity in agricultural landscapes, which is, however, accompanied by critical barriers to the broad acceptance and regular use of such technologies by farmers. Only if based on adequate legal and financial political framework, which create incentives for solution-focused cooperation among all relevant stakeholders and allow a user-orientated technology development, can DSTs develop their underlying potential and gain acceptance among farmers.

1. Introduction

Europe is one of the world's most intensively cultivated landmasses. Agricultural areas, including pastures, arable lands, and mosaic farmlands, cover 39% of Europe's total land area (European Environment Agency, 2023a). Various studies have revealed that agricultural activities are the main drivers of the loss of natural habitats and species diversity (European Environment Agency, 2023b). Since the 1950s, when agricultural practices started to intensify, European landscapes and especially nature conservation areas around agricultural land have been characterised by a significant and ongoing loss of plant and animal species. As presented in the latest European Environment Agency Report, between 2013 and 2018, 60% of European biogeographical habitats were in inferior or poor condition (European Environment Agency, 2020). In addition to habitat fragmentation, intensive use of pesticides and fertilisers is considered the main perpetrator of biodiversity loss (Forschung für nachhaltige Entwicklung, 2019). In particular, common farmland birds, such as skylarks or starlings, and general insect species richness are negatively affected (Habel et al., 2019; European Environment Agency, 2021). Additionally, the increased use of nitrogen promotes the growth of plant species that respond positively to a greater nitrogen supply and replace slower-growing, site-specific and ecologically significant wild field herb species (Deutsche Akademie der Technikwissenschaften et al., 2020). These ecological developments contrast with the constantly increasing food demand from a rising world population. UN experts estimate that the population will increase to 8.5 billion by 2040 (UNRIC-Regionales Informationszentrum der Vereinten Nationen, 2023). Therefore, in addition to further major influencing factors, such as climate change, agriculture faces the challenge of meeting increasing food requirements without jeopardising vital natural habitats and their inherent biodiversity (Hrustek, 2020; Jeanneret et al.,

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Abbreviations

ASSAs	Agricultural service supply agencies
CAP	Common Agricultural Policy
CS	Civil Society
CSAP	Citizen Science Applications and Platform
DIP	Digital Information Platform
DSTs	Digital and smart technologies
DTGS	Digital Technology for Agricultural Guidance and Steering
FMIS/DSS	Farm Management and Information System/Decision Support System
F	Farmer
FR	Field Robot
FU	Federal Funding Agency
I	Industry
P	Politics/Politicians
R	Researcher
Sensor	Sensor Technolog
UAV/UAS	Unmanned Aerial Vehicle/Unmanned Aerial System

2021).

Digital and smart technologies (DSTs) are considered a promising approach for developing solutions to the predicament of creating sufficient food production and, at the same time, biodiversity-conserving agriculture (Abbasi et al., 2022). "Agriculture 4.0", "smart farming" or "digital farming" refers to the introduction of disruptive, partially communications-derived technologies, such as big data, artificial intelligence, or autonomous robotic systems/field robotic technologies, into agriculture (Ghobakhloo, 2020; Abbasi et al., 2022). After the Green Revolution (Agriculture 2.0), the adoption of DSTs in agriculture became the characteristic feature of a new and upcoming agricultural era. In this context, the advent of "precision farming" (Agriculture 3.0) in the early 1980s indicated the start of digital transformation with the broader use of DSTs, such as in the form of guidance systems or yield monitoring. Based on advances in computing and electronics, precision farming tools have provided options for saving energy in machinery use, irrigation water and chemicals applied in the field (Dayioğlu and Turker, 2021; Mohr and Kühl, 2021). The ongoing evolutionary stage of Agriculture 4.0 is characterised by end-to-end connectable, knowledge-based farm production systems, autonomous farming technologies, cloud computing, and big data analytics (Dayioğlu and Turker, 2021; Zscheischler et al., 2022). In the context of our study, DSTs include an array of hardware- and software-based digital technologies used for arable farming. Their further categorisation into seven subcategories was adopted from the study of (Krachunova et al., 2024). These categories are based on mode of operation and adapted for the context of nature conservation and ecosystem service provisioning. Hence, the selected DSTs may not be developed in the intention to protect biodiversity, but we analysed their possible application to protect biodiversity.

The expectations discussed in the literature on DSTs regarding their contribution to reducing the negative environmental impacts of agriculture are high. As an overall objective, digitalisation is assumed to contribute to greater flexibility, efficiency, effectiveness and automation of processes; to increasing savings; and to enabling faster decision-making (Hrustek, 2020). With the help of digital agricultural systems, fertiliser, pesticide, and water use can be more precisely controlled. By monitoring soil parameters and weather conditions, sensors and cloud computing support smart irrigation solutions, control of insect attacks and pesticide use. The great advantage of DSTs is precise, tailored, and real-time area management. Fleets of drones or ground vehicles, for example, can significantly reduce pesticide use via real-time detection systems (Hrustek, 2020). Additionally, temporal, spatial, and individual data can be gathered, processed, analysed and combined with other information to guide site- or plant-specific management decisions and thereby strengthen the efficiency, productivity, quality, profitability and sustainability of agricultural production (Dayioğlu and Turker, 2021).

DSTs also possess great potential to foster the direct implementation of conservation measures in agricultural landscapes (Basso and Antle, 2020; Mouratiadou et al., 2023). With the further development of complex biomonitoring systems to ensure soil biodiversity and good soil conditions, for example, agriculture can actively drive the sustainability and conservation of biodiversity (Hrustek, 2020). In addition to easier monitoring, DSTs can significantly facilitate the provision of information and the planning and documentation of valuable conservation measures in agricultural landscapes (Geppert et al., 2023). To date, DSTs that specifically promote the realisation of nature conservation measures are only rarely available on the market (Kliem et al., 2022). Representative examples can be found outside of Europe in the USA with the Agricultural Conservation Planning Framework (ACPF). ACPF is an ArcGIS toolbox-based concept for agricultural watershed management, developed by the USDA's Agricultural Research Service in partnership with the USDA Natural Resources Conservation Service (Tomer et al., 2017). Based on high-resolution elevation data together with a specially developed database, land use, crop history, soils information, and site-specific conservation practices for the protection and improvement of water quality within agricultural landscapes can be identified (Tomer et al., 2020).

However, despite the technically possible ecological advantages of DSTs, the crucial point of their actual contribution and effectiveness in biodiversity-friendly agriculture depends on their acceptance and application by farmers (Mohr and Kühl, 2021; Zscheischler et al., 2022). In addition to the simple demotivating factor of the acquisition and maintenance costs of DSTs, digitalisation is accompanied by unintended side effects, uncertainties and undesirable risks and changes (Zscheischler et al., 2022). For farmers, the use of DSTs involves consideration of their possible advantages and disadvantages in terms of additional costs, time requirements and actual management as well as production effects (Michels et al., 2020; Shang et al., 2021). Some of the main factors and concerns mentioned by farmers in various studies include data privacy and safety, perceived usefulness, compatibility, sufficient infrastructure and information, and increased vulnerability to internal system failures during the use of DSTs in everyday farm businesses (Garske et al., 2021; Mohr and Kühl, 2021; Shang et al., 2021; Zscheischler et al., 2022).

To support the broader adoption and application of DSTs in agriculture for the revitalisation of biodiversity, a better understanding of their potential advantages and the barriers they may face is necessary. This is the aim of this paper, which offers a comprehensive analysis of stakeholders' perceptions of the actual contributions of and barriers to the use of DSTs to enhance biodiversity while elucidating the status quo and providing valuable insights into future application directions. Adopting a two-level stakeholder exchange based on an online survey and an expert discussion, we fill a research gap by applying a stakeholder-based approach in the analysis of the underlying potential of and barriers for DSTs with respect to enhancing biodiversity in Germany. Analogical approaches have been conducted in the USA by analysing farmers' perceptions and dispositions to conservation targeting when receiving targeted conservation options for their fields identified by ACPF and conservation planners (Ranjan et al., 2020a). Complementary, Ranjan et al. (2020b) and Ranjan et al. (2022) focused on the barriers and opportunities in the use of ACPF as well as education and training needs for the use of several decision support tools by different groups of conservation agency staff and planners. In contrast to these studies, we not only analyse the barriers, but explicitly focus on the experienced and expected potentials of DSTs regarding biodiversity by the participating stakeholders.

To gain a multilayered and comprehensive overview by means of our stakeholder analysis, we considered the viewpoints of farmers and other relevant representatives, such as agents from politics, research and industry. This study evaluates and presents i) the potential of DSTs to actively support the implementation of nature conservation measures and therefore strengthen biodiversity in agricultural landscapes and ii) the remaining challenges and tasks that must be addressed to increase the acceptance of DSTs by target users. The findings allow us to draw conclusions on ways to enhance the potential of DSTs to support biodiversity in agricultural landscapes and resolve the administrative, political and technical challenges currently hindering broader adoption and application of DSTs.

2. Materials and methods

2.1. The German case

Germany is the second-largest agricultural producer in Europe after France (German Trade and Invest, 2024). In 2020, 50.6% of Germany's land area was used for agriculture (BMEL, 2022). Within Central Europe, Germany is one of the countries with the highest density of cattle and swine (Eurostat, 2022). In particular, in regions with high livestock density, nitrogen and phosphorus surpluses cause water eutrophication. Nutrient inputs and the resulting deterioration of aquatic ecosystems are in conflict with the European Union (EU) Nitrates Directive (Council Regulation (EC)) and the Water Framework Directive (Directive 2014/101/EU; Garske et al., 2021). Water eutrophication is often accompanied by further negative environmental impacts, such as soil degradation. Here, DSTs can offer valuable approaches to mitigating such ecological pollution and help Germany avoid paying high financial penalties to the EU (Garske et al., 2021; BMEL, 2023; Zinnbauer et al., 2023). In addition to water eutrophication, Germany must mitigate further negative environmental impacts caused by its high agricultural inputs. With regard to biodiversity, the results of (Hallmann et al., 2017) showed a decline in aerial insect biomass of 82% during mid-summer and a seasonal loss of 76% in 63 nature protection areas in Germany over 27 years. In addition, 53% of the almost 600 wild bee species in Germany are currently endangered (Hallmann et al., 2017; Deutsche Akademie der Technikwissenschaften et al., 2020; Pfiffner, 2022). A strong decline in insect biomass and species affects further species in the food chain and crucial pollination processes of plants (Pfiffner, 2022). These diversity losses are confirmed by (Gatti et al., 2023), who showed that Germany lags behind most of the 27 member states of the EU (in third-to-last place, only ahead of Belgium and Denmark) with regard to strictly protected areas, according to the International Union for Conservation of Nature.

After the USA and China, Germany is the world's third-largest producer of agricultural machinery (German Trade and Invest, 2024). Despite Germany's worldwide significance with regard to agricultural machinery production, the current state of digitalisation in German agriculture remains far from the goal of linking, collecting and documenting data in a barrier-free way along the value chain via a cross-corporate data hub (Munz et al., 2019). According to the latest results of the monitoring programme of the European Commission on digital progress for a number of different indicators within the member states, Germany's Digital Economy and Society Index (DESI) value was 52.9 in 2022. This value corresponds to the middle of the range among the EU countries (EU average: 52.3) (European Commission, 2022). However, Germany is in second-to-last place (19%) among all EU countries with regard to nationwide deployment of a fibre-optic infrastructure and the latest mobile communications standards (European Commission, 2023). As indicated by (Schweikert, 2019), improving digital framework conditions in Germany is crucial. For example, the lack of data linkage and availability impede the improved usability and stronger dissemination of digital applications at the national level.

Germany is of great economic and agricultural significance within the EU and one of the world's leading producers of agricultural machinery, but it has shown slow progress in digitalisation compared to other EU member states. The individual environmental impacts of German agriculture, such as the nitrogen surplus, have been the subject of intense debates in the EU parliament and require a sustainable national solution. For these reasons, Germany represents an appropriate case study with respect to the purposes of this research.

2.2. Online survey

The online survey was targeted at all stakeholder groups considered relevant for our analysis. The first group included farmers and agricultural service supply agencies (ASSAs). ASSAs represent a prevalent practice in German agriculture, in which companies provide commercial services for farmers, such as harvest, fertilisation or seeding. By drawing on ASSAs, farmers can compensate for non-existent machines on their farms, missing time, or employees. Since ASSAs conduct the same work and are faced with the same problems in the field as farmers, they were added to stakeholder group one. For farmers, three different categories were distinguished i) traditional conventional farming, ii) conventional farming with reduced input of fertilisers and pesticides and a strong orientation toward the codes of good farming practice and iii) organic farming. The second stakeholder group included representatives from politics/governmental administrations, various associations (agricultural, nature conservation, landscape management), and nongovernmental organizations (NGOs). The third group included experts from research and businesses other than agriculture. A fourth group was added for all other participants of the survey who could not assign themselves to one of the three other stakeholder groups. The participants of group four followed the same question path as the farmers and ASSAs. However, the outcome of the data they provided only made up a small part of the overall results. Therefore, their responses were not considered in the further evaluation of the results.

The questionnaire was divided into four main sections (Appendix A1):

1) assignment to the stakeholder group;
2) previous experience with DSTs, including barriers experienced in their use;
3) expected potentials from the use of DSTs, in general and with regard to nature conservation in particular;
4) sociodemographic data.

We adopted DSTs categorisation from Krachunova et al. (2024). In this study, categorisation of the DSTs was based on three overlapping sub-area characteristics of the Federal Ministry of Education and Research in Germany as a starting point: 1) the use of software-driven equipment, 2) the use of farm management software; and 3) the collection, storage, and networking and analysis of data. These three main categories were further distinguished to their original mode of operation: software- and hardware-based technologies. Thereof resulted a categorisation of seven technology types in total:

a) software-based: 1) farm management information systems and decision support systems (FMIS/DSS); 2) digital technologies for guidance and steering (DTGS); 3) digital information platforms (DIP); 4) citizen science applications and platforms (CSAP)
b) hardware-based: 5) sensor technologies (sensors); 6) field robots (FR) 7) unmanned aerial vehicles and systems (UAV/UAS).

Using the four-part questionnaire structure, the survey was created with multiple paths, with each path addressing one of the different stakeholder groups. In the framework of this study, we evaluated only a selected number of questions relevant to our research question (Appendix A1). The original questionnaire consisted of 45 questions (summarised in Appendix A1).

Potential participants were identified via research- and business networks of ZALF, EFI Commission and the ZEW – Leibniz Centre for European Economic Research in Mannheim, personnel linked to the EFI Commission. This resulted in 4, 337 contacts. The survey link was distributed by e-mail invitation in four invitation rounds (16 May, 23 May, 5 June, 16 June, 2024) to attract a large number of responses. The online survey was administered from 16 May - 30 June, 2023 via LimeSurvey (LimeSurvey Expert, Cloud version 5.6.25, released 2023). At the end of the survey duration of 45 days, 142 questionnaires were fully completed, adding up to a response rate of 3,27%. The collected data were exported from LimeSurvey and transferred into MS Excel for descriptive statistical analysis.

2.3. Expert discussion round

The expert discussion round, designed as a focus group discussion, aimed to generate more detailed qualitative information from the stakeholders to complement the quantitative results of the online survey. We invited 30 experts from different disciplines: farmers (F), research (R), politics (P), federal funding agency (FU), civil society (CS) and industry (I). Of the invited experts, 13 accepted the invitation and participated in the discussion, which was held online via Zoom (Version: 5.16.10 (26186)) on the July 3, 2023 from 9:30 a.m. to 12:30 p.m. in Germany. The group of experts consisted of five researchers (R1, R2, R3, R4, R5), two representatives from civil society (CS1, CS2), two politicians (P1, P2), one farmer (F1), one representative from a federal funding agency (FU1) and two employees from industry (I1, I2). The experts' identities are kept anonymous, but the results presented are ascribed to the area of expertise of the participants (Tables 1 and 2, Appendix A2). The experts invited to participate in the discussion by e-mail in advance were introduced to the overall aim and background of the study before the discussion round.

The structure of the discussion round was based on three main topics:

1) Potentials of DSTs
   - 1.1 How do you assess the potential of DSTs to contribute to sustainable agriculture?
   - 1.2 Where do you see the greatest potential?
   - 1.3 What potential do you see for DSTs in terms of promoting/protecting biodiversity in agricultural areas?
2) Challenges/barriers in the application of DSTs
   - 2.1 Where do you see the greatest difficulties/obstacles in establishing the application of DSTs in agriculture (in crop production)?
3) Necessary measures/changes to overcome existing challenges in the application of DSTs
   - 3.1 What specific measures must be taken to overcome these obstacles?
   - 3.2 In your opinion, what political framework conditions would be required for DSTs to overcome the greatest obstacles?

Before discussing each of the three topics, we presented the corresponding results of the online survey as a discussion starting point. In advance of discussing topic (1), we showed the results for the survey questions "How high do you estimate the potential of DSTs for sustainability and environmental protection in agriculture over the next ten years?" and "In terms of implementing measures to protect biodiversity, where do you see the greatest potential for DSTs?". Before discussing topic (2), we presented the results of the survey questions "What factors hinder or prevent the use of DSTs for your activities?" and "With regard to the protection of biodiversity in agricultural areas, where do you see the greatest remaining challenges for the continuous, regular use of DSTs?". The discussion of topic (3) was based on the insights gained from the overall discussion and used to summarise the relevant discussion points.

In parallel to the online discussion, participants were provided the

Table 1
Summary of the expert discussion: Part 1 "Potentials of DSTs" (frequency of stakeholder statements per question).

Number of answers	1.1 How do you assess the potential of DST to contribute to sustainable agriculture?	1.2 Where do you see the greatest potential in relation to 1.1?	1.3 What potential do you see for DSTs with regard to the promotion/protection of biodiversity in agricultural land?
5			
4	Optimisation of resource use (R1, R2, R3, F1) ("*more efficient use of pesticides and fertilisers*") (CS1)		
3		Site-adapted management (R2, CS1, I1)	
2	Digital Twin (R1, R4) Site-adapted management (R1, R4) Documentation (P1, R2) Information availability/overview (R2, R4) Optimised cooperation and data exchange between farmers and authorities (P1, R2) Improving biodiversity (R4, I1) Time efficiency (R4, F1) ("*DST not solitary solution! →embedding in context DST highly specific tool: if basic conditions are adequate (legal, financial + technical): high potential*") (P1, CS1)	Optimisation of resource use (R1, P1) Precision farming (R1, I1) Standardisation (R4, CS1) ("*technical interfaces between systems for quick & easy problem solving*") (P1) Time efficiency (P1, I1) ("*time advantage most and more important for farmer, not financial*") (F1) Improved planning & decision-making (R2, F1) (→ "*technology open approach!*") (FU1)	Optimise species protection with field robots (R1, R4) Optimised cooperation and data exchange between farmers and authorities (R2, F1) ("*returning feedback, fluent data exchange authorities must implement a service concept (F1) → clear, technology-open support to farmers; information: which technologies work, which don't → develop + offer manifold advisory services (from individual consultation to agricultural application*")) (CS1, F1)
Specific statements/ examples	("*shared agricultural data space with clear options and data sovereignty for farmers (also linked to research!): data collection to improve overall efficiency, access to all! data from administration side via open data; time stamps to get access to past measures. Interfaces must be resilient (via APIs or connectors in the agricultural data room!). Farmer has to return information to authorities (e.g. position history on meadow*") (F1)		("*strategic land use planning: combination of (semi-) natural landscape elements with extensive land use*") (CS1) ("*smart, easy-to-use solutions providing direct, individual answers in the field (currently too much effort for the back office") (F1)* ("*public financing very important: society places certain demands on* *farmers (species protection, climate change, food security), therefore, technical tools must be provided for implementation (for ALL farms*") (F1) ("*established "Geobox": data only managed by authorities; no access for farmers; operational information of farms should not be kept there!*") (F1) ("*time registration (as fourth dimension) of specifically applied measures in the field, in addition to a 3-dimensional model registration of the applied measures in field*") (F1)

n = 13; CS: Civil Society; F: Farmer; FU: Federal Funding Agency; I: Industry; P: Politics/Politicians; R: Research.

Table 2
Summary of the expert discussion: Part 2 "Barriers to DSTs and options to overcome them" (frequency of stakeholder statements per question).

Number of answers	2.1 Where do you see the greatest difficulties/barriers in establishing the application of DSTs in agriculture (in crop production)?	3.1 What specific measures must be taken to overcome the barriers?	3.2 In your opinion, what political framework conditions would have to occur, to overcome the greatest obstacles?
5	No standardisation yet (R1, R2, R3, P1, F1)		
4			Create open access to (high-quality) data and programmes (R1, R2, R3, F1)
3	Access to software (R1, P1, I1)	Standardisation among the federal states (R1, R3, CS1) More user-friendliness (R1, R2, F1)	
2	No centralised overview of existing data/information (R1, P1) Provision of training (P1, I1) ("*development of a network of lighthouse farms in regions, farmers share their valuable knowledge with other farmers, but lighthouse farms must be remunerated accordingly!*") (F1) User-friendliness (R2, CS1) Standardisation of the federal states Data-security (R3, P1) ("*better selectivity + data sovereignty*") (F1) Economic viability (R4, I1) ("*single DSTs are available, have to be matched and promoted by the market*") (CS1)	Centralisation (R1, CS1) ("*connect existing technologies*") (CS1, F1) Offer training (R2, F1)	Create federal institution in charge of digitisation of agriculture (R1, R2) Organise standardised training opportunities in all states (R2, CS1) ("*intercorporate training, working groups and workshops!*") (R2) Connect/include all stakeholders (R1, CS1) ("*e.g. authorities and lighthouse-farm-network or technology-savvy farmers*") (P1) Offer consulting (R2, CS1)
Specific statements/ examples			("*Currently: digitalisation (especially sensor technology and robotics) offers support also for small and medium farms with regard to labour shortages*") (R4)

n = 13; CS: Civil Society; F: Farmer; FU: Federal Funding Agency; I: Industry; P: Politics/Politicians; R: Research.

opportunity to answer the discussion questions in written form on an online-shared Excel sheet. The sheet was also accessible for several hours after the discussion with the aim of obtaining answers from all the experts, including those who were less talkative during the Zoom meeting. The experts' answers were analysed qualitatively in a manner that enabled developing inductive categories from them. We used the answers provided on the Excel sheet and the comments from the participants' Zoom meeting.

All text passages relevant to the research question were collected and coded. To enhance trustworthiness in qualitative data, inter-coder reliability was conducted. Two authors paraphrased the transcription independently form each other. The resulting paraphrases were subsumed by generalisation and translated into codes (Appendix A2). The predefined codes were then compared with the original transcription by each of the two authors and in a second step among both authors. Discrepancies were aligned and adjusted in agreement. For better overview and orientation, subsumed and generalised codes were arranged in a table and sorted in descending order by number of mentions (Tabl. 1 and 2). Individual expert statements and arguments provided during the online discussion that were particularly relevant and informative were quoted (although shortened due to space limitations) and integrated into Table 2 according to the appropriate paraphrases. These attached quotations were not added to the total number of provided answers in each row (first column, Tabl. 1 and 2).

3. Results

3.1. Online survey

3.1.1. Demographics

The majority of the 142 survey participants were farmers (34%), followed by researchers (25%), employees from other companies (18%), stakeholders from politics/governmental administration (11%), employees in associations/NGOs (7%), others (5%) and ASSAs (1%). In terms of gender, a clear majority were male, with only just over 10% female and approximately 1% nonbinary. Most participants were 56–66 years old, followed by 36–45 years (23%), 25–35 and 46–55 years (both 22%). Less than 1% were under 26 years of age, and only approximately 2% were over 66 years of age. The most represented degree was a university diploma (32%), followed by a PhD (23%) and a professional school degree (19%).

Approximately one-tenth held a degree not listed in our survey; an even smaller proportion held a master's degree (7%), followed by a bachelor's degree (6%) and apprenticeship/vocational training (3%). Geographically, the majority of the participating stakeholders came from Saxony (18%), the second-most-common origin being Lower-Saxony (15%), followed equally by Baden-Wuerttemberg and Bavaria (both 13%) and North Rhine-Westphalia (10%). Berlin, Bremen, Hamburg and Saarland were not represented. Stakeholders represented 3–5% of all remaining German federal states. Farmers and ASSAs were predominantly specialised in arable farming (37%), with livestock farming (22%) and grassland management (21%) in second and third place, respectively, and approximately 10% in horticulture and other agricultural areas. With regard to the underlying farm operation model, 40% were managing their farms according to EU-organic farming standards, 33% according to conventional farming with reduced use of fertilisers and plant protection products, and approximately 27% according to classic conventional farming.

3.1.2. Experiences in the use of DSTs and the application of nature conservation measures

According to farmers and ASSAs, the most frequently used DSTs categories are FMISs/DSSs and DTGSs, both achieving 19% daily usage and significant shares of weekly usage (Fig. 1). The second-most-commonly used technology is DIPs, with 4% daily usage. CSAPs and sensors also account for 4% of daily usage, but this percentage is offset by more than 70% of responses indicating that these technologies are neither used nor planned for use. The least-used DSTs for farming activities are FRs, with 83% of respondents answering that they are not using them or planning to use them. UAVs/UASs are also not used or planned for use by more than half of the respondents, but approximately one-quarter of respondents use them occasionally, and another quarter plans to deploy them.

FMIS/DSS: Farm Management and Information System/Decision Support System; DTGS: Digital Technologies for Agricultural Guidance and Steering; DIP: Digital Information Platform; CSAP: Citizen Science Application and Platform; Sensors: Sensor Technology; FR: Field Robot; UAV/UAS: Unmanned Aerial Vehicle/Unmanned Aerial System.

The farmers and ASSAs affirming to use DSTs at all (Fig. 1) were asked more concretely about the purposes of DSTs application in

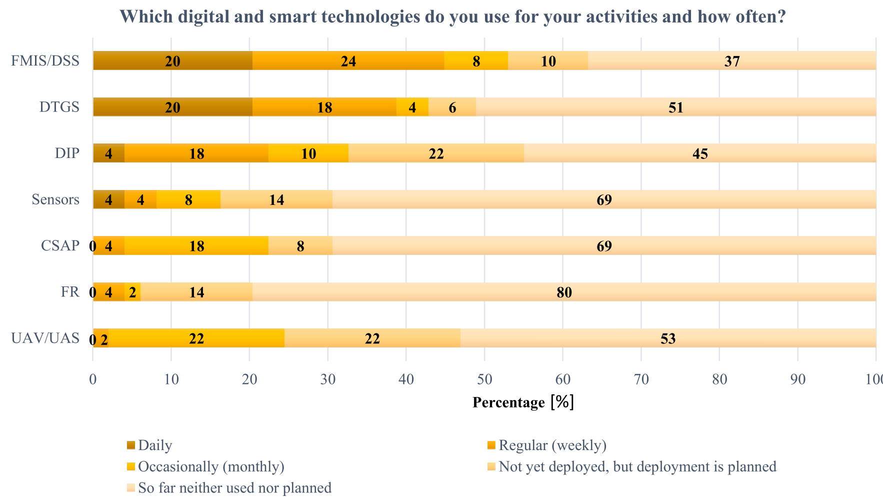

Fig. 1. Indicated frequency of use of DST categories by farmers and ASSAs. The total number of farmers and ASSAs is n = 49.

agriculture, and the results showed that 90% of these stakeholders used DSTs for improved operational management on farms (Fig. 2). As the second-most-indicated application field of DSTs, these stakeholders already specified the implementation of regulations on environmental protection, followed by monitoring of fields. Slightly more than half of the stakeholder groups of farmers and ASSAs named the advantages of supportive decisions through data-driven analytics and the reduced use of environmentally harmful substances as current fields of DSTs application. The least prevalent areas for DSTs use were the promotion and protection of biodiversity as well as the improvement of soil structure, with only slightly more than 40% of farmers and ASSAs responding positively to these application categories.

To receive an assessment of the previous experience of farmers and ASSAs with the implementation of environmental and conservation measures, they were asked for their frequency of implementation to date. The environmental and conservation measures were defined as measures included in the subsidy programs of the Common Agricultural Policy (CAP) of the EU. The CAP defines a common agricultural policy for all EU member states though each member state still shows additional, nationally specified laws. In Germany, national laws are even further broken down to federal state level (European Commission, 2024). Conservation measures listed in the subsidy programs of the CAP involve, for example, particularly sustainable practices in arable farming or for annual special crops (*e.g.* planting of hedges or structurally rich flowering and protection strips with annual sowing) as well as on permanent grassland (*e.g.* resting periods for the protection of breeding wildlife or abandonment of fertilisation) (Niedersächsisches Ministerium für Umwelt and Energie und Klimaschutz, 2024).The majority of farmers and ASSAs had already implemented environmental and conservation measures on-farm on a yearly basis (80%) (Fig. 3). A smaller proportion of respondents in this stakeholder group had implemented them twice, once, in a different rhythm, or not yet (4–6%) (Fig. 3).

3.1.3. *Barriers to the use of DSTs*

According to farmers and ASSAs, the greatest obstacle to the daily use of DSTs are compatibility issues among technologies from different vendors (Fig. 4). The respondents indicated that the high acquisition costs of DSTs were the second-largest obstacle, followed by data security concerns. An increased maintenance effort, a general lack of interest in DSTs or a lack of user-friendliness of DSTs were regarded as smaller

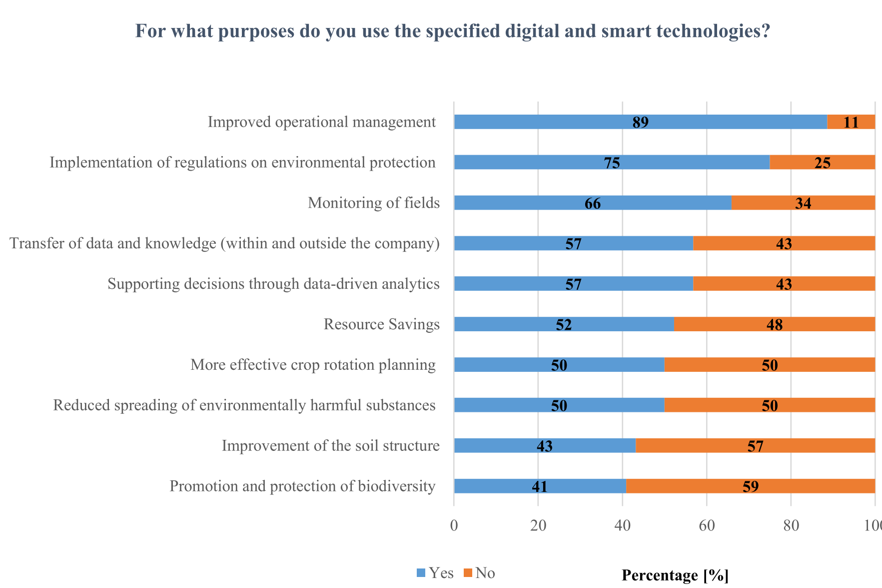

Fig. 2. Indicated current application areas of DSTs by farmers and ASSAs in agricultural practice. The total number of farmers and ASSAs is n = 44.

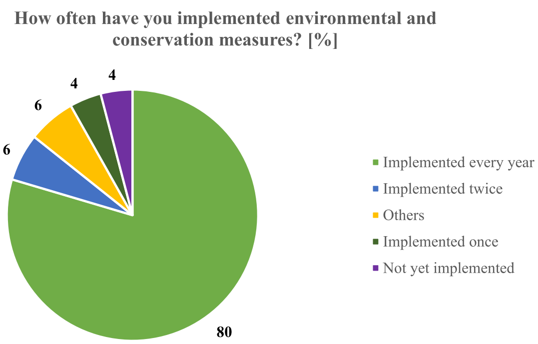

Fig. 3. Indicated frequency of implementation of environmental and conservation measures of farmers and ASSAs. The total number of farmers and ASSAs is n = 49.

impediments to the use of DSTs in daily agricultural practice. The smallest obstacles are absent deployment opportunities for DSTs and having little digital literacy, basic education or experience in the use of DSTs. Altogether, organic operating farms showed significantly higher barriers regarding high acquisition costs of DSTs, increased bureaucratic effort, missing user-friendliness and the complex operation of DSTs compared to traditional conventional farms and conventional farms with reduced input of fertilisers and pesticides and a strong orientation towards the codes of good farming practice.

According to stakeholders from politics/governmental administration, associations, NGOs, and experts from research and business other than agriculture, compatibility issues between technologies from different vendors were also perceived as the most notable preventing factor for the regular use of DSTs in German agriculture (Fig. 5). This impediment was followed by an unstable internet connection and a lack of user-friendliness of DSTs. The smaller obstacles these respondents noted were too complex DST operation demands or an additional or increased bureaucratic effort required using DSTs. As the smallest impediments, these stakeholder groups indicated a lack of deployment opportunities for DSTs and increased maintenance requirements for DSTs.

3.1.4. *Challenges in the use of DSTs for the protection of biodiversity in agricultural areas*

Although DSTs are already regularly applied for the implementation of nature conservation measures (Fig. 2), their use for the protection of biodiversity in agricultural areas remains arduous, according to farmers and ASSAs (Fig. 6). The greatest remaining challenges are the absence of

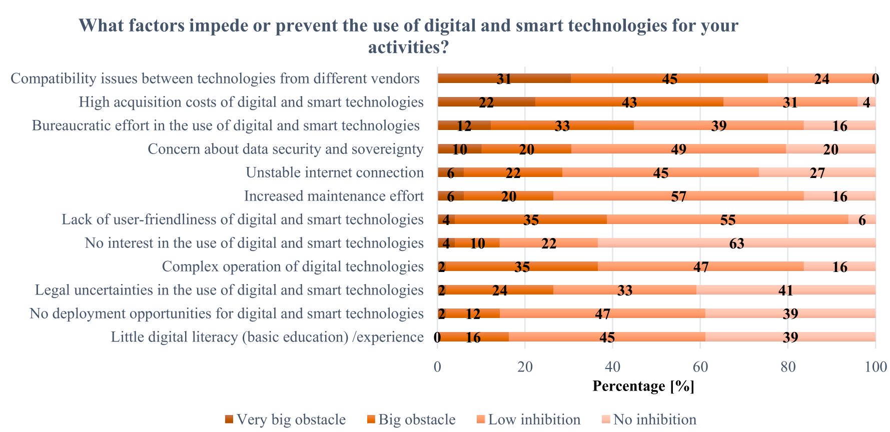

Fig. 4. Indicated prevention factors for the use of DSTs in agriculture according to farmers and ASSAs. The total number of farmers and ASSAs is n = 49.

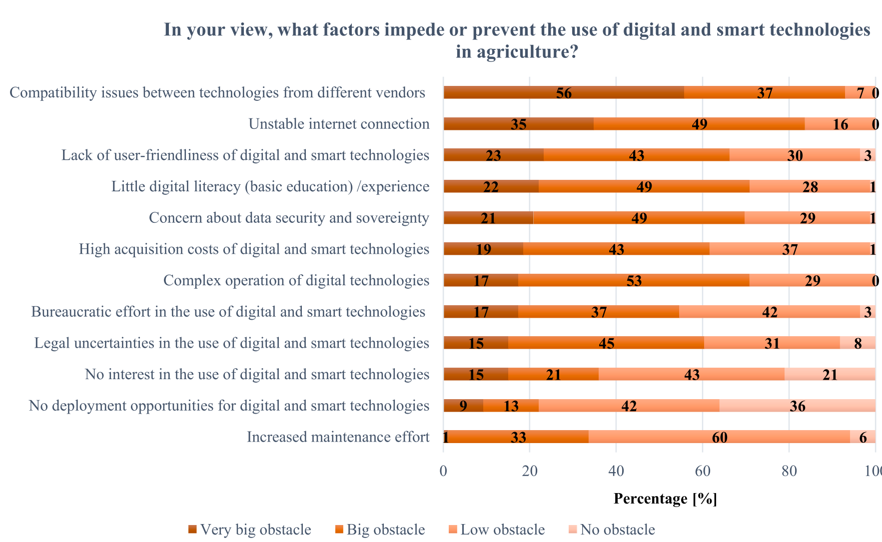

Fig. 5. Indicated preventing factors for the use of DSTs in agriculture according to stakeholders from politics/governmental administration, associations, NGOs, and experts from research and business other than agriculture. The total number of these stakeholders is n = 86.

digital communication processes at local authorities/ministries for data transfer, followed directly by a lack of compatibility between digital devices and established technologies. These stakeholders would also appreciate the availability of advisory services and comprehensive information on the use of DSTs in the field of nature conservation and environmental protection, with three-quarters indicating the lack of this support as a very large to large challenge. Especially organic operating farms indicated this deficiency as a big challenge. The immature digitalisation within the CAP is a less substantial but still important obstacle.

3.1.5. Potentials of DSTs in terms of implementing measures to protect biodiversity

The majority of farmers and ASSAs saw a very high or high potential for DSTs to support the protection of biodiversity via the simplified transmission of documented proof of implemented measures and more effective (site-specific) conservation options (Fig. 7). The provision of better-prepared information options by DSTs as well as a contribution to the mitigation of sanction risks acted out by the controlling authorities via more precise cultivation were acknowledged as areas with high potential for DSTs by more than half of the respondents in this stakeholder group. The smallest but still significant potential was perceived for the use of DSTs to save time during the application, planning, implementation and documentation of conservation measures.

3.2. Expert discussion

In the first part of the discussion round "Potentials of DSTs" (Tabl. 1), we asked the experts how they assess the potential of DSTs to contribute to sustainable agriculture. The most frequent reply (R1, R2, R3, F1) was the optimisation of resource use (Tabl. 1). Among the less-often mentioned potentials were documentation, information availability/overview or optimised cooperation and data exchange between farmers and authorities. Regarding the direct impact of DSTs on field composition, two experts mentioned enhanced side-adapted management according to the natural site conditions of agricultural areas (R1, R4) and an improvement in biodiversity (R4, I1) (Tabl. 1). In further questioning regarding the greatest potential of DSTs to contribute to sustainable agriculture (1.2, Tabl. 1), side-adapted management was cited as the most recognised and applied method to date (R2, CS1, I1). In addition, two experts cited optimised resource use (R1, P1), precision farming (R1, I1), standardisation (R4, CS1), time efficiency (P1, I1) and improved planning and decision-making (R2, F1) (Tabl. 1). With the third question (1.3), we wanted to obtain a statement from the experts on the potential of DST to promote/protect biodiversity in agricultural land. As Table 1 shows, the greatest potential (two references) was observed for optimised species protection with FRs (R1, R4), as well as optimised cooperation and data exchange between farmers and authorities (R2, F1). Experts also recommended that attention should be given to "*the implementation of a service concept on the part of the authorities, including returning feedback and fluent data exchange*" (F1) and therefore providing "*clear, technology-open* support *to farmers*" (CS1, F1) (Table 1). Regarding the daily application of DSTs, a significant simplification should be considered since users require "*smart, easy-to-use solutions providing direct, individual answers in the field (currently too much effort for the back office)*" (F1) (Table 1).

In the second half of the discussion round "Barriers to DSTs and options to overcome them" (Tabl. 2), we started with question 2.1 regarding where the experts perceive the greatest difficulties/barriers in establishing the application of DSTs in agriculture (in crop production) to be. Notably, statements from five experts (R1, R2, R3, P1, F1) addressed a lack of standardisation (Tabl. 2). Three replies referred to onerous access to software (R1, P1, I1). A lacking centralised overview of existing data/information (R1, P1), the provision of training (P1, I1), user-friendliness (R2, CS1), standardisation among Germany's federal states (R2, I1), data security (R3, P1) and economic viability (R4, I1) were regarded as comparatively lower impeding factors (Tabl. 2). However, in terms of training options, a valuable approach would be the "*development of a network of particularly digitally advanced pioneer farms,"lighthouse farms", in regions, by which farmers share their valuable knowledge with other farmers. However, lighthouse farms must be remunerated accordingly*" (F1). Question 3.1, regarding which specific measures must be taken to overcome these barriers, was most frequently answered by implementing standardisation among the federal states (R1, R3 CS1), together with more user-friendliness (R1, R2, F1) (Tabl. 2). In addition, two experts (R1, CS1) underlined a need for centralisation ("*connect existing technologies*") (CS1, F1) and increased provision of training (R2, F1). In the last question of the expert discussion round (3.2), we wanted to determine which political framework conditions would have to occur to overcome the greatest obstacles. One of the most-often mentioned suggestions (four experts) was to create open access to high-quality data and programmes (R1, R2, R3, F1). In addition, two experts recommended the creation of a federal state institution in charge of digitisation of agriculture (R1, R2), the organisation of standardised training opportunities in all states (R2, CS1) ("*intercorporate training, working groups and workshops*") (R2), a connection/inclusion of all stakeholders (R1, CS1) (with an emphasis on the lighthouse-farm

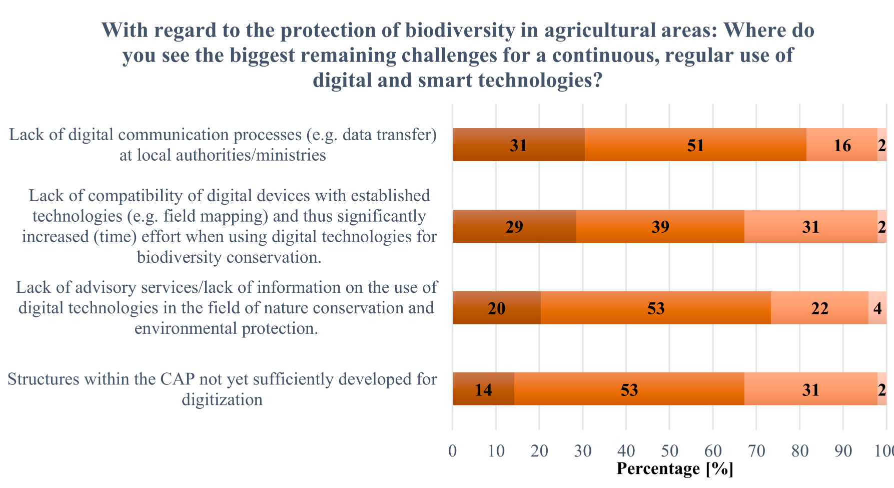

Fig. 6. Indicated remaining challenges for the regular use of DSTs to foster biodiversity in agricultural areas according to farmers and ASSAs. The total number of farmers and ASSAs is n = 49.

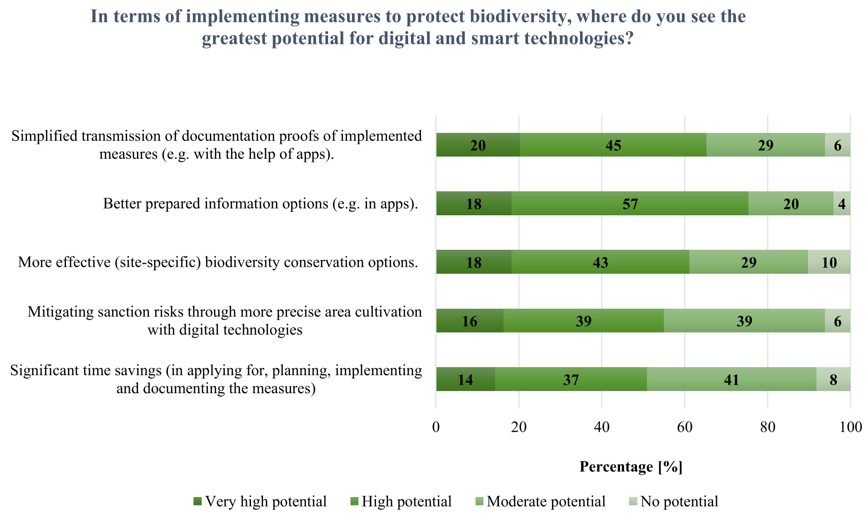

Fig. 7. Indicated potential of DSTs to contribute to the protection of biodiversity in agricultural landscapes according to farmers and ASSAs. The total number farmers and ASSAs is n = 49.

approach: "*e.g., authorities and lighthouse-farm-network or technology-savvy farmers"* (P1)) and consulting (R2, CS1) (Table 2). However, against all barriers, R4 indicated that "*digitalisation (especially sensor technology and robotics) offers* support *also for small and medium farms with regard to labour shortages*" (Table 2).

4. Discussion

Prior to the overall discussion, we would like to take up the small response rate of the online survey again. With 3,27% and a duration of 45 days, it might only represent a general trend regarding the acceptance of DSTs in German agriculture. Nevertheless, we were able to attract a broad diversity of agricultural stakeholders to participate. In addition, as well the online survey, as the expert discussion were undertaken between May and July, a very busy period for all agricultural stakeholders. Taking these circumstances into account, the spectrum and results of our stakeholder analysis are still of great significance and value to the overall research gap.

The profile of the participants of our stakeholder analysis showed a strong accent on male researchers and farmers, between 56 and 66 years old and holding a higher education qualification such as diploma or PhD. Farmers and ASSAs had profound experience with the implementation of environmental and conservation measures (Fig. 3).

A total of 75% of farmers and ASSAs indicated that they had already used DSTs for the implementation of regulations on environmental protection, and an additional 41% affirmed the deployment of DSTs for the direct promotion and protection of biodiversity (Fig. 2). The greatest potential of DSTs to contribute to the protection of biodiversity was seen in the simplified transmission of documented proof of implemented measures, for better-prepared information provided by DSTs, as well as more effective (site-specific) conservation options (Fig. 7). These results coincide with the findings of (Kliem et al. (2022), Geppert et al. (2023) and Basso and Antle (2020).

However, crucial barriers and obstacles still exist towards a more common use of DSTs for regular farm management tasks as well as for the enhancement of biodiversity. The biggest barriers resulting from our stakeholder analysis are a lack of standardisation and centralisation. Notable examples are the non-compatibility of DSTs from different vendors, a lack of standardised access to information, and data as well as differing application procedures within the 16 German federal states (Figs. 4 and 6 and Tabl. 2). Relating to farmers and ASSAs, the non-existing cooperation between different vendors is frequently accompanied by concerns about data security and sovereignty (Fig. 4). These constraints and apprehensions are based on the fact that a few major agribusinesses dominate the current market for agricultural technology and hold all sensitive farm data of technology users (Clapp and Ruder, 2020). Farmers and ASSAs fear the exposure of internal affairs of their farm management (Tabl. 1) since they have little control over the processing of their data (Soma and Nuckchady, 2021). In addition, economic viability of DSTs is limited under such circumstances (Tabl. 2). Technological lock-in effects might occur because lower costs of adoption in the short run reinforce the use of popular and dominant technology systems (Clapp and Ruder, 2020). R1, P1, and I1 also noted the onerous access to software as a key obstructive factor (Tabl. 2). The incompatible variety of DSTs market offers by major agribusinesses provide mostly one-sided solutions and do not show any form of individual user requirements alignment. Several scholars point to the inequalities in the distribution of power, since these market hegemonies limit farmers' decision making and significantly constrain their access to and impartial overview of individually suitable DSTs (Clapp and Ruder, 2020; Hackfort, 2021; Soma and Nuckchady, 2021). According to R2 and I1, consistent procedure among the 16 German federal states could be achieved by, among other things, standardising the application programmes for agricultural subsidies, as well as the creation of a centralised overview of existing data/information (R1, P1) (Tabl. 2). As the second-greatest factor preventing a more regular adoption and use of DSTs farmers and ASSAs named the high acquisition costs of DSTs (Fig. 4). These results correlate with the outcomes of Kernecker et al.'s (2020) analysis of farmers' perceptions of smart farming technologies across seven European countries (Kernecker et al., 2020). An increasing prevalence of DSTs can be observed on large commodity crop farms embedded in industrialised country settings (Clapp and Ruder, 2020). This development is confirmed by analyses from Gabriel and Gandorfer (2023), Soma and Nuckchady (2021), and Hackfort (2021), expounding the necessary financial investments on the farmers' part to deploy DSTs on their farms. However, considering the broad spectrum of DSTs, low cost mobile technologies or apps free of charge might not be affected by these restrictions (Soma and Nuckchady, 2021), whereas our results show that especially CSAPs are among the least used DST categories so far (Fig. 1).

Nevertheless, financial factors do apply to more complex and costly DSTs such as automated artificial intelligence controlled smart farming systems or FRs (Soma and Nuckchady, 2021; Krachunova et al., 2024). Due to high acquisition and maintenance costs, which are not yet offset by the management or production advantages of most of the DST categories, small-holder farmers might be left behind or experience pressure to purchase expensive DSTs to keep up and still operate successfully on the market (Munz et al., 2019; Duncan et al., 2021; Hackfort, 2021; Kliem et al., 2022). Affordability does not only play a role in terms of acquisition costs, but also relating to maintenance costs, including the payment of skilled employees that are qualified to adequately operate DTSs (Duncan et al., 2021; Hackfort, 2021). Besides affordability, access to sufficient digital infrastructure and connectivity is of great importance for a profitable deployment of DSTs on farms. Our results show, farmers and ASSAs evaluated an unstable internet connection as the fifth most impeding factor for the use of DSTs (Fig. 4), while stakeholders from politics/governmental administration, associations, NGOs, and experts from research, and business other than agriculture even rated it as the second most impeding factor (Fig. 5). Farmers located in very remote and inaccessible rural areas can be disadvantaged and unable to realise the full potential of available DST offers and solutions for agriculture (Hackfort, 2021). An adequate digital infrastructure is also needed for all administrative processes and interactions between farmers and authorities. Farmers and ASSAs indicated the lack of direct and easily accessible communication channels currently as one of the greatest challenges for a regular use of DSTs to foster biodiversity in agricultural areas (Fig. 6). As the findings of (European Commission (2023) and (Schweikert (2019) show, to achieve true digitalisation at all levels, Germany especially still has a long way to go. However, missing digital infrastructure and transactions might not only be the result of national structural deficiencies, but also the result of non-existent or insufficient training of agency staff as well as farmers (Fig. 6 and Tabl. 2). During our expert discussion, participants of all stakeholder groups agreed on the need for standardised training opportunities on the various application opportunities of DSTs for biodiversity revitalisation purposes, along with a stronger connection of all relevant stakeholders through a centrally organised network (Tabl. 2). A total of 73% of farmers and ASSAs indicated a lack of advisory services/a lack of information regarding the use of DSTs in the field of nature conservation and environmental protection as a very big to big challenge (Fig. 6). These findings coincide with the results of (Ranjan et al. (2020a and 2022) and Kernecker et al. (2020), stating the importance of educational offers and trainings to reduce the barriers of farmers as well as of conservation agency staff towards the deployment of DSTs for nature conservation purposes.

As indicated by the stakeholders from politics/governmental administration, associations, NGOs, and experts from research and business other than agriculture, a lack of user-friendliness of DSTs also plays a major role in reinforcing users' barriers and restraints towards a more regular deployment of DSTs in agriculture (F1) (Fig. 5, Tabl. 1). Reasons such as low market maturity and therefore a lack of economic viability as applying to FRs, do significantly reduce users' receptiveness to give these DST categories a chance for trial (Kliem et al., 2022; Gabriel and Gandorfer, 2023; Heitkämper et al., 2023; Fragomeli et al., 2024).

The central recommendation of our experts how to overcome existing barriers concerned the need for standardisation. In addition to technological compatibility and stronger collaboration among developers, authorities, and users in the development of DSTs to improve their user-friendliness, centralised and standardised management, provision and access to data across Germany is highly needed. First studies on possible options for the realisation of a governmental digital data platform have already been conducted by (Bartels et al., 2020). Further needs include adequate and coordinated training options for users, preferably in the form of intercorporate workshops (Tabl. 2). The experts clearly considered politics to have the responsibility to provide the necessary framework conditions, a view supported by the suggestion of R1 and R2 to create federal institutions in charge of the digitisation of agriculture programmes (Tabl. 2). For farmers, testing new technologies is associated with economic risk. On this count, public support through a resilient infrastructure and public financing are very important (F1) (Tabl. 1). The need for targeted training and provision of information does especially apply to organic operating farms. Our results indicated that organic farms show higher barriers and greater concerns towards the adoption of DSTs. These findings coincide with the findings of (Vasiliev, 2021), who investigated the use of DSTs among organic farmers in Latvia. With the aim to reduce the environmental impacts of agriculture and meet the biodiversity and sustainable targets of the UN and the EU, the share of organic operating farms will increase significantly in and beyond Europe over the next few decades. To keep up with the latest market developments and do not get outcompeted by conventional operating farms, targeted training and information to allow a broader application of DSTs are crucial for organic operating farms (Vasiliev, 2021). In this study we analysed the barriers to the application of DSTs and focused on their experienced and expected potentials regarding the enhancement of biodiversity in agriculture. Nevertheless, considering the potential of DSTs must be accompanied by taking into account the eventual risks and side-effects DSTs might cause in agriculture. Within the proponents' argumentation, DSTs improve and lower significantly the resource consumption of agricultural operations (Dayioğlu and Turker, 2021; Fragomeli et al., 2024; Garske et al., 2021). However, these effects might get offset by the energy and resource requirements of the DSTs themselves. Recent studies (Clapp and Ruder, 2020) investigated the high energy demand of DSTs for machinery and cloud servers. In addition, cloud servers are characterised by high water consumption and data centres produce high amounts of heat loss, favouring global warming (Krachunova et al., 2024). DSTs depend on specific raw materials such as gold, iron ores or other rare earth elements. Exploitation of these materials can cause severe contaminations of soils, rivers and groundwater and mineworkers quite often work under dangerous and legally inadmissible conditions. Especially rare earth elements occur only in a small number of countries, leading to dependencies on certain states, which are not desirable under the current geopolitical situation (Geppert et al., 2024). Due to a short durability and currency, most DSTs are quickly worn-out and generate considerable amounts of e-waste (Clapp and Ruder, 2020).

Critics further argue that DSTs only deepen the dependence on industrial agriculture and intensify prevalent highly productive, one-sided food production systems. Instead of becoming a digital utopia, without deliberate and strong policy, progressing digitalisation in agriculture might turn into a digital dystopia (Daum, 2021). Critics consider DSTs hampering the way for a profound and required transformation towards sustainable agriculture by pushing other approaches such as agroecology into the background (Clapp and Ruder, 2020; Daum, 2021). DSTs might even multiply existing problems by provoking unintended side-effects, which must be solved by the next technological innovation (Clapp and Ruder, 2020).

Other parts of the opposing debate focus on the social and cultural impacts DSTs might have on agriculture. Replacing former manual work with new technologies can lead to job losses, a shift in qualification requirements and eventually fewer job opportunities for those, who live in rural areas (Sparrow and Howard, 2021). These developments might even exacerbate unequally distributions of wealth within rural areas (Sparrow and Howard, 2021). Moreover, DSTs might influence the image of agriculture and the way people think about the natural world as well as food and farming and lead to alienation. Particularly FRs can change consumers' expectations of "perfect food" and cause more food waste based on unmet visual and qualitative expectations (Sparrow and Howard, 2021).

Digitalisation and the use of DSTs is associated with security risks in every area, including agriculture. Cyber-attacks, hacking and sabotage are some of the main externally caused risks. Internally, DSTs might lead to internal system failures on individual farms, multiplying the amount of work to fix the damage incurred (Geppert et al., 2024).

To avoid a digital dystopia and the above-mentioned negative economic, social, and cultural impacts of DSTs, politics must set the right incentives and create the framework to turn digital agriculture into an opportunity for nature and society. Furthermore, research and industry must cooperate, and development of DSTs has to focus on sustainability criteria to prevent side-effects.

Considering such ideal preconditions, we wish to highlight our results regarding the potentials of DSTs to enhance biodiversity in agricultural landscapes. So far, DSTs are already being applied to implement nature conservation measures by users, who perceive a clear advantage in a simplified transmission of documentation proofs, more effective (site-specific) conservation options and better-prepared information options. Furthermore, DSTs are considered to contribute to the mitigation of sanction risks through more precise area cultivation (Fig. 7). The benefit of significant time savings during the application, planning, implementation and documentation of conservation measures is more a secondary than deciding factor for the application of DSTs.

5. Conclusion and perspectives

Based on the survey results together with our expert discussion, we showed that DSTs have the overall potential to contribute to the enhancement of biodiversity in agricultural landscapes.

Nevertheless, critical barriers must be overcome to increase their acceptance, reduce unintended side-effects, and establish DSTs as easy-to-use, standard farming technologies. Crucial obstructive factors, such as a lack of standardisation, centralisation and communications are an outcome of an inadequate political framework. Knowledge and expertise regarding the creation of viable and beneficial DSTs are available but they must be unified, standardised and centralised. Politicians bear the responsibility to establish the legal and financial framework and incentives that will enable research, industries and farmers to work together and benefit from each other's expertise. In this regard, federal coordination represents a main issue to address in Germany. To achieve a reliable and sustainable digital reform for the revitalisation of biodiversity in agriculture, a top-down approach should be replaced by a bottom-up approach, beginning from the users' needs and demands regarding DSTs in their daily business. It also involves a direct link between politicians and farmers, as well as farmers and industries to enable appropriate and direct response and adjustment to the changing needs and requirements of DST users and prevent DSTs development towards the profit of major agricultural companies instead of the various users' needs. The priority focus for all concepts and intentions must be on the adherence of sustainability criteria and for the benefit of nature and society. Particularly in view of biodiversity and landscape management, farmers are embedded in social structures in which society places high demands. To prevent a digital dystopia and help agriculture escape from a negative image as a source of environmental pollution, responsible technical solutions, shaped and supported by all agriculturally relevant stakeholders and the society are needed. DSTs are not a standalone solution for solving the problems of biodiversity decline and species loss in agricultural landscapes. However, they represent a valuable supporting tool that can contribute to reducing the prevalent concerns of farmers about bureaucratic hurdles related to the application of nature conservation measures and help make these legal guidelines more transparent and easier to manage at the national as well as European level.

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CRediT authorship contribution statement

Frauke Geppert: Writing – original draft, Resources, Methodology, Funding acquisition, Data curation, Conceptualization. **Tsvetelina Krachunova:** Writing – review & editing, Resources, Methodology, Funding acquisition, Data curation. **Ioanna Mouratiadou:** Writing – review & editing, Supervision, Methodology. **Julia von der Nuell:** Visualization, Resources, Data curation. **Sonoko D. Bellingrath-Kimura:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.indic.2024.100444.

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