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Original Research

The Digital Agricultural Knowledge and Information System (DAKIS): Employing digitalisation to encourage diversified and multifunctional agricultural systems

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ABSTRACT

Multifunctional and diversified agriculture can address diverging pressures and demands by simultaneously enhancing productivity, biodiversity, and the provision of ecosystem services. The use of digital technologies can support this by designing and managing resource-efficient and context-specific agricultural systems. We present the Digital Agricultural Knowledge and Information System (DAKIS) to demonstrate an approach that employs digital technologies to enable decision-making towards diversified and sustainable agriculture. To develop the DAKIS, we specified, together with stakeholders, requirements for a knowledge-based decision-support tool and reviewed the literature to identify limitations in the current generation of tools. The results of the review point towards recurring challenges regarding the consideration of ecosystem services and biodiversity, the capacity to foster communication and cooperation between farmers and other actors, and the ability to link multiple spatiotemporal scales and sustainability levels. To overcome these challenges, the DAKIS provides a digital platform to support farmers' decision-making on land use and management via an integrative spatiotemporally explicit approach that analyses a wide range of data from various sources. The approach integrates remote and *in situ* sensors, artificial intelligence, modelling, stakeholder-stated demand for biodiversity and ecosystem services, and participatory sustainability impact assessment to address the diverse drivers affecting agricultural land use and management design, including natural and agronomic factors, economic and policy considerations, and socio-cultural preferences and settings. Ultimately, the DAKIS embeds the consideration of ecosystem services, biodiversity, and sustainability into farmers' decision-making and enables learning and progress towards site-adapted small-scale multifunctional and diversified agriculture while simultaneously supporting farmers' objectives and societal demands.

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1. Introduction

The global agricultural sector faces mounting challenges as it is expected to simultaneously meet food security demands, absorb market shocks, support green energy and bio-economy transitions, become climate neutral, and avoid harmful environmental impacts. This multiplicity of diverging pressures and demands may give rise to conflicts between crop productivity and profitability on the one hand and the provision of biodiversity and ecosystem services (ESS) on the other. In theory, diversified agricultural systems designed to enhance ecosystem multi-functionality should be able to better address such diverse targets, in particular at the landscape level, by producing multiple amenities while supporting biodiversity and ecosystem health and resilience [1–3]. In practice, successful design and implementation of such systems are exceedingly difficult due to the many complex social, economic, political, and environmental factors influencing land use decisions and ecological processes in agricultural landscapes. However, using digital technologies can provide critical, innovative support to redesign agricultural systems successfully within their specific spatial setting and foster new learning in agricultural decision-making [4].

Digitalisation in agriculture has gained momentum over the past decades, with numerous technologies fast emerging and made available to the academic and farming communities. Remote and *in situ* sensing, artificial intelligence (AI), autonomously operated machines, and online data collection and communication platforms offer new ways towards understanding, managing, and monitoring agro-ecosystems and the agri-food value chain. In particular, Decision Support Systems (DSSs) aiming at data collection and processing to inform farm management decisions [5,6] are becoming increasingly comprehensive in response to the need for communication and data exchange and to meet the requirements of different stakeholders [7].

Concurrently, the potential benefits of agricultural digitalisation to support sustainable agriculture transformations are gaining attention among scientists, policy-makers, and other relevant actors. Indeed, technological innovations, such as the use of *in situ* and remote sensing technologies for precision agriculture applications, may contribute to significant resource use efficiency improvements (e.g., for fertilizer, pesticide, or water application) and reduced greenhouse gas (GHG) emissions [8,9]. Nevertheless, at present, an opportunity gap remains in regards to (i) the systems-oriented integration of large available datasets documenting interconnected field- and landscape-scale processes and (ii) integrative analysis and translation of such data into actionable crop management options [8,10].

Moreover, the relationship between the deployment of digital technologies and the promotion of sustainable agricultural systems is not void of scepticism. Topics under debate include the role of digitalisation in ameliorating trade-offs between different ESS [11], its implications for sustainable development [12,13], and its contribution in social science research [14]. There are concerns that digitalisation in agriculture could perpetuate conventional industrial agricultural and food systems and the associated negative environmental impacts [11], potentially undermining the uptake of agro-ecological approaches [12]. Moreover, the potential of new digital technologies to involve citizen science or other participatory methods has largely remained unused in the technology development cycle [15].

In this context, the deployment of digital agriculture, when intersecting with established modes of decision-making, needs to consider new demands for sustainability and aim at harnessing synergies towards new learning opportunities in the Agricultural Knowledge and Innovation System (AKIS) [4]. In developing future AKISs, which are key concepts for communication and interaction between various actors in the agricultural sector for innovation processes [16], the role of digitalisation is acknowledged as a core issue [17]. This is because it is expected to affect connectivity, transparency, and governance of agricultural knowledge and advice networks [18], as well as to directly stimulate new collaborations and space for experimentation with the wider society [15].

Here, we present the Digital Agricultural Knowledge and Information System (DAKIS) as a novel and systems-oriented data-integration framework that leverages digital technologies to support highly complex and innovative decision-making, explicitly supporting multifunctional and diversified agriculture. Based on an iterative exchange with stakeholders and consortium members and a literature review on digital agriculture tools, we identify and present underlying requirements based on which we developed the DAKIS. Subsequently, we present the DAKIS' structure and components. The DAKIS is a digital knowledge-based DSS that integrates remote and *in situ* sensors, AI algorithms, and online web platforms with publicly available real-time databases, farm economics planning modules, modelling of ESS and biodiversity, agent-based modelling, stakeholder-based stated demands, and sustainability impact assessment. We then highlight its principal novelty: the integration of diverse digital agriculture methods and technologies to provide decision support which simultaneously (i) incorporates ESS and biodiversity into farmers' decision-making processes; (ii) fosters communication and cooperation between farmers and other actors; and (iii) links multiple spatiotemporal scales and broader sustainability levels.

2. Materials and methods

To develop the DAKIS, we first identified the requirements for a novel tool that, on the one hand, promotes the integration of biodiversity and ESS provision (e.g., erosion control, climate and water regulation, carbon storage, or recreation) in decision-making processes, and on the other hand is concurrent with progress on the development of digital tools in the scientific and commercial communities. We identified the core requirements through an iterative process of exchange with stakeholders and the consortium members (Section 2.1) and, in parallel, identified the limitations of existing tools via a literature review (Section 2.2). With these requirements and limitations in mind, we developed the DAKIS conceptual and technical architecture and designed a proof of concept exemplified via a use case for establishing grassland buffer patches (Section 2.3).

2.1. Iterative process to establish the requirements for the DAKIS

We prioritized a participatory approach building on knowledge co-production to ensure the development of a relevant and applicable tool aligning user requirements, scientific novelty, and policy relevance [19]. Specifically, we applied an iterative design process, see for example Gbangou et al. [20], during which we conducted eight semi-structured meetings and workshops (WSs) with stakeholders (Table S1) and another 15 with consortium members (Table S2). The interaction with stakeholders was facilitated via the establishment of two Stakeholder Advisory Boards (StABs) in two case study regions in Germany (Bavaria and Brandenburg), allowing a continuous process of evaluating and improving the DAKIS throughout its development (see Table S3 for information on the members of the DAKIS StABs). The case studies were selected to reflect differences in landscape and pedoclimatic characteristics, field size and arrangements, and local politics and societal needs, thus aiming to illustrate different stakeholder requirements and develop a tool that applies to diverse circumstances. The process provided input into the specification of the scope and functionality of the DAKIS (users, aims, functions, thematic and spatiotemporal scopes). The results of this exchange also guided the selection of criteria used for the literature review, described in Section 2.2.

2.2. Literature review on digital agriculture tools

In parallel with the iterative exchange with stakeholders and consortium members, we conducted a systematic literature review [21] of peer-reviewed publications describing digital science-based and commercial tools (Fig. 1). Through our review, we aimed to ensure that the DAKIS makes a novel contribution to the pool of existing approaches for decision-making. The review focused on tools in the proximity of the DAKIS overall scope, i.e., generic and whole-system approaches that automatically collect and process information to support decision-making for designing agricultural systems and landscapes.

First, we conducted a web search on Scopus, Science Direct, and Google search engines to ensure science-based as well as commercial digital agricultural tools are covered, using keywords such as ‘digital agriculture’, ‘farm management system’, ‘digital tools’, and ‘digital decision support’ (see Table S4 for the list of search strings used for the literature review). From a list of 643 digital tools, we excluded duplicates as well as tools and technologies that were not directly relevant to agricultural practice and biodiversity or ESS-related topics.

Next, we screened the abstracts (scientific literature) and websites (commercial literature) presenting the remaining 237 digital tools. We excluded those that were too specific in terms of geographical scope (e.g., only one region) or thematic coverage (e.g., only vineyards or only irrigation) and those that had no advanced features to support decision-making (e.g., only sensing technologies).

We evaluated the remaining 42 tools to select principal examples for an in-depth review. We selected tools that are more complete in terms of the functions that they support (i.e., at least two of the functions outlined below), more advanced in terms of technology development (i.e., integration of sensor data and/or AI), and ensure a representation of both science-based and commercial tools. We focused on functions that were identified as key requirements for the DAKIS (see also Section 3.1):

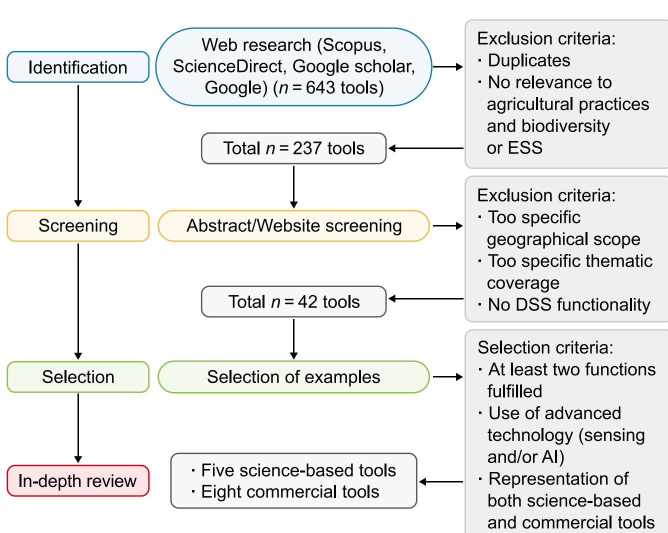

Fig. 1. PRISMA flow diagram depicting the literature review process on digital agriculture tools.

(i) Monitoring of production, biodiversity, and ESS: this function provides critical information to improve yield, biodiversity and other ESS delivery and can assist in establishing and implementing result-based policy measures.
(ii) Decision support for farm operations and management: this function aims at simplifying and optimizing farmers' decision-making, ideally considering the delivery of ESS, biodiversity, and sustainability and considering the complex and diverse expectations from agricultural production.
(iii) Support of communication and collaboration: to foster the valorisation of ESS and biodiversity and overall the cooperation and communication between farmers and other actors (citizens, civil society, consumers, etc.), this function encourages partnerships to meet societal demands on biodiversity and ESS.

We evaluated the shortlisted tools in detail with respect to their thematic scope, spatiotemporal scales, functions, and employed technologies. Regarding thematic scope, we looked at the inclusion of production, environmental, economic, and social dynamics in terms of the tool's capacity to represent relevant processes and provide information on associated impacts. To evaluate the tools' coverage of different spatiotemporal scales, we distinguished five spatial scales (sub-field, field, farm, landscape, and higher levels which include regional, national, value chain, global, etc.) and four temporal scales (real-time high resolution such as hourly or daily, average yearly, multi-year consisting of several average years, long-term analysis in the direction of foresight). In terms of technologies, we evaluated the uptake of both diagnostic and prescriptive methods [9], across digital tools, including remote and *in situ* sensing, AI, and advanced decision-making models. We note that these different technologies are not seen as alternatives since they often complement each other (e.g., monitored data can be used by decision-making algorithms to generate management recommendations).

2.3. Development of the DAKIS architecture and proof of concept

For the development of the DAKIS architecture, we used a design thinking approach, see for example Plattner et al. [22], involving the consortium members to establish the overall conceptual and technical architecture, as well as the interfaces between its different components. That aimed to ensure the effective cooperation of diverse disciplines and the development of a conceptually and technically sound approach. To achieve this, in addition to monthly meetings within and across the project work packages, we held regular weekly or monthly meetings of thematic task forces (e.g., management design, database design, decision-making processes, and indicators).

To provide a proof of concept of the DAKIS, the tool is currently being tested in two agriculturally very different test regions in Brandenburg and Bavaria in Germany. While the Brandenburg test region is more monotonous and characterised by large fields, the Bavaria test region has significantly smaller plots and more structural elements. Here, we demonstrate the approach for the Brandenburg test region via a simple use case based on the establishment of grassland buffer patches. This allows testing the conceptual and operational validity of the connections between the different DAKIS components. The use case replicates the technical application of a user interacting with the DAKIS based on desired functionalities and selected management recommendations. To construct the use case while testing the applicability and validity of different DAKIS components, we are working on several experimental areas. These include two landscape windows (5 km $\times$ 5 km) in Märkisch-Oderland and Oder-Spree to map the supply of and demand for biodiversity and ESS potentials, as well as different experimental fields to monitor the differentiated provision of ESS (see also Section 3.3.3 for a description of the relevant DAKIS components). The experimental fields cover aspects related to small-scale patch cultivation (patchCROP experimental field), grassland systems (Paulinenaue experimental field), and agroforestry systems (Löwenberg experimental field).

3. Results

3.1. Requirements for the DAKIS

Through active discussions in a series of workshops and consultations, stakeholders and consortium members provided key requirements for the users, aims, and functions of the DAKIS, as well as its thematic and spatiotemporal scopes (see Table 1, Table S5 provides further detail on the outcomes of the stakeholder exchange).

Iterative consultations strongly underlined the importance of recognizing and prioritizing farmers as core users and beneficiaries of the tool while ensuring compatibility with the visions of relevant stakeholders (farmers, civil society, policy makers, and others). Stakeholders and consortium members agreed on three overall aims for the DAKIS, which flowed into formulating the tool's central three functions. First, considering the multi-functionality of diversified agricultural systems was identified as a central management objective for future agricultural systems. A consequent second aim is the consideration of ESS and biodiversity as a required component for farmers' decision-making processes. Finally, stakeholders expressed strong interest in DAKIS functionality focused on learning and exchange. These considerations are reflected in the three central functions which underpin the overall DAKIS development: (i) monitoring production, biodiversity, and ESS provision; (ii) decision-support for farmers for ESS, biodiversity, and sustainability; and (iii) enhancing communication and collaboration among farmers and other stakeholders (see Section 2.2 for extended definitions).

To address these aspirations, the DAKIS needs to harness the opportunities offered by digital technologies by adopting a broad thematic scope encompassing the production, environmental, and socio-economic dimensions of sustainable agriculture. Therefore, it needs to consider a range of key pedoclimatic, economic, policy-relevant, and socio-cultural aspects that influence farmers' land use and management decisions. Further, it needs to provide impact assessments for a broad range of ESS and biodiversity outcomes related to proposed land-management options while capturing and integrating ESS and biodiversity provision datasets with sustainability demands from different stakeholders and land managers.

Requirements regarding the temporal and spatial coverage of the DAKIS pointed towards the need to develop solutions addressing aims across multiple spatial scales and time horizons. Both ESS and biodiversity provision and demand need to be formulated at sub-field, field, farm and landscape scales in a spatially explicit manner. The DAKIS will facilitate site-specific

Table 1
Requirements for the DAKIS according to the iterative process with stakeholders and consortium members.

Requirement	Source meeting(s)
Users	
Farmers are the core users of the DAKIS and the central beneficiaries of its functions.	StAB meetings (2020, 2021)
The DAKIS scope and interface are compatible with the visions and demands of stakeholders (farmers, civil society, policy makers and others).	Foresight WS 2017 Stakeholder WSs 2017 StAB meetings (2020, 2021)
Overall aims	
Facilitate the design of multi-functional diversified agricultural systems.	Foresight WS 2017 Stakeholder WSs 2017
Integrate ESS and biodiversity provision into farmers' decision-making process.	Stakeholder WSs 2017 StAB meetings (2020, 2021)
Foster new learning and exchange in the AKIS.	Stakeholder WSs 2017
Functions	
Monitor production, biodiversity, and ESS provision.	Foresight WS 2017 Stakeholder WSs 2017 StAB meetings (2020, 2021)
Enhance decision support for farmers on agricultural production, management design, and planning, considering the provision of biodiversity and ESS, economic feasibility, and social dynamics.	Foresight WS 2017 Stakeholder WSs 2017 StAB meetings (2020, 2021)
Enhance communication and collaboration among farmers and other stakeholders.	Foresight WS 2017 Stakeholder WSs 2017 StAB meetings (2020, 2021)
Thematic scope	
Represent locally-relevant production, environmental, economic, and social dynamics and cover the full spectrum of provisioning, regulating, and cultural ESS (see definition in Ref. [23]) and biodiversity and their trade-offs.	Foresight WS 2017 Stakeholder WS 2017 StAB meetings (2020, 2021)
Take into account both farmers' preferences (e.g., trade-offs for sustainability goals, the feasibility of implementing farm-management options), and societal demands regarding ESS and biodiversity provision.	Foresight WS 2017 Stakeholder WS 2017 StAB meetings (2021)
Spatiotemporal scope	
Consider the sub-field level to allow the design of small-scale spatially and functionally diversified systems and account for variability across temporal resolutions.	Foresight WS 2017 Stakeholder WS 2017 StAB meetings (2020)
Operate at the farm level to allow operational planning and strategic decision-making from farmers' perspectives.	Foresight WS 2017 Stakeholder WS 2017 StAB meetings (2020)
Link to the landscape level to investigate the effects of landscape features and processes and explore the potential for cooperation between different stakeholders.	Foresight WS 2017StAB meetings (2020)
Consider regional or national contexts and links to wider sustainability targets and impacts to allow reflection beyond the farm decision-making level and in the longer term.	Foresight WS 2017 Stakeholder WSs 2017

optimization recommendations, thus allowing end-users to align agricultural decisions (e.g., on crop type and management practices) to minimize trade-offs and conflicts. By considering neighbouring or non-farm actors' preferences, collaborative agricultural actions can also be facilitated and better targeted across farm boundaries or landscapes. Lastly, the DAKIS should fulfil the requirement of taking a wider societal perspective by considering immediate as well as long-term impacts on regional and national sustainability objectives.

3.2. Literature review findings on digital agriculture tools

As awareness of the utility of technological and digital applications has grown among agricultural scientists, there has been a concurrent rapid increase in the number and scope of science-based and commercial tools leveraging digital technology advancements for improved farm management [7,24,25]. Based on screening 42 digital agriculture tools, we recapitulate a clear tendency to focus on monitoring activities (40/42 tools) often related to production optimization purposes (Table S6). Data generated by monitoring are frequently employed further together with decision-making algorithms to provide farmers with decision support on the design and planning of farm operations and management (30/42). Only 14/42 tools support communication and collaboration among farmers and other actors. With respect to technologies, 21/42 tools use remote sensing-based data, 22/42 tools include monitoring data via *in situ* sensing, and 8/42 tools consider AI to meet their demands for agricultural decision support.

The screening process resulted in a list of 13 tools (Table S7) that we reviewed in greater depth with respect to their thematic and spatiotemporal scopes, their functions, and the adopted digital technologies. These are 365FarmNet [26], Agricolus [27], Agricon [28], Conservis/ClimateFieldView [29,30], CropSat [31], FarmersEdge [32], FarmNET [33], LandCaRe [34], NaLamKi [35], NEXT Farming [36], SMAG [37], Topcon Agriculture Platform (TAP) [38], and Trimble Farmer Pro/Advisor Prime [39].

3.2.1. Thematic and spatiotemporal scopes

The representation of production processes and outcomes is central in all tools, which all consider crop production and some also livestock production (Fig. 2, see Table S8 for details on the thematic scope). Almost half of the tools explicitly consider environmental aspects, such as soil health, GHG emissions, biodiversity, and water quantity and quality. However, most tools focus on selected environmental aspects due to precision farming, with only a few presenting a wider set of environmental effects to the user. Economic aspects are well reflected in some of the tools, which provide a farm economic analysis component focusing on, e.g., farm stocks, gross margins and income, financial plans, and cost summaries for various operational scenarios and reporting features. Social aspects, such as collaboration between different actors or contribution to achieving the sustainable development goals (SDGs), are not represented directly.

The well-represented production focus within the tools is also reflected in the spatiotemporal resolution (see Table S9 for details on spatiotemporal aspects). Production dynamics are focused on aggregated yearly planning, with some representation of real-time high-resolution management, multi-year, and long-term effects and planning at sub-field, field, and farm levels. Environmental impacts, when considered, are typically linked to production at the sub-field to the farm level and are seldom addressing larger impacts on a landscape scale. Considering economic dynamics, selected tools consider these in short- and long-term perspectives at the farm level, depending on the specific focus of individual tools.

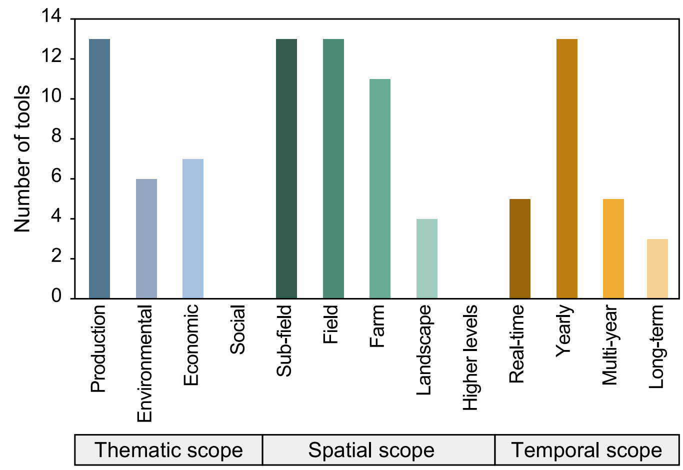

Fig. 2. Number of tools supporting different thematic and spatiotemporal scopes among the shortlist of reviewed digital agriculture tools.

3.2.2. Functions and technologies

Our findings on the function of monitoring production, biodiversity, and ESS provision show that all tools emphasize increasing yields and production levels (Fig. 3a, see Table S10 for details on the tools' functions). This is achieved via monitoring plant health and detecting stressors (e.g., crop disease, water stress) to prevent negative impacts on yields and improve input efficiency. The digital monitoring activities are satellite-based, complemented by Unmanned Aerial Vehicles (UAVs), real-time data collected via on-farm weather stations, vehicle-mounted N sensors, field robotic mounted sensors, and *in situ* soil sensors (Fig. 3b, see Table S11 for details on employed technologies). The digital technologies presented often complement each other. In fact, data collected by sensing technologies are further analysed by using models and AI. Non-automated soil sample collection complements the monitoring activities. Considering the monitoring of biodiversity and ESS, few attempts exist where monitoring data are used as input for carbon offsetting purposes rewarded by civil society or to enhance biodiversity protection via, e.g., UAV-based fawn detection. Some tools emphasize their capability to monitor farm activities and management data for reporting purposes to comply with regulatory frameworks and subsidy receipt or certification standards (e.g., GMO-free, organic). However, in general, the tools show a rather clear focus on monitoring production levels and providing management documentation for regulation and standard compliance instead of monitoring the delivery of ESS and biodiversity.

Considering the function to provide on-farm decision support on the planning of farm operations and management, tools often build on monitoring data to create maps and statistics on yield and vegetation indices and/or use modelling approaches to optimize seeding and harvesting processes and propose site-adapted and precise pesticide and fertilizer applications. Also, they often collect and analyse farm economic data for documentation and accounting or to explore the economic outcome of a certain management suggestion. This is typically achieved via cost-performance calculations, profit contribution calculations, or other cost summaries for various operational scenarios. However, tools do not provide recommendations on the menu of land use and investment decisions that maximize revenue while meeting the potential for ESS and biodiversity. Consequently, the integration of ESS and biodiversity is not directly reflected in farmers' decision-making processes. The target indicator is usually yield, while resource-use efficiency improvements are welcomed, and environmental indicators for ESS and biodiversity, when considered, are presented as a side-product

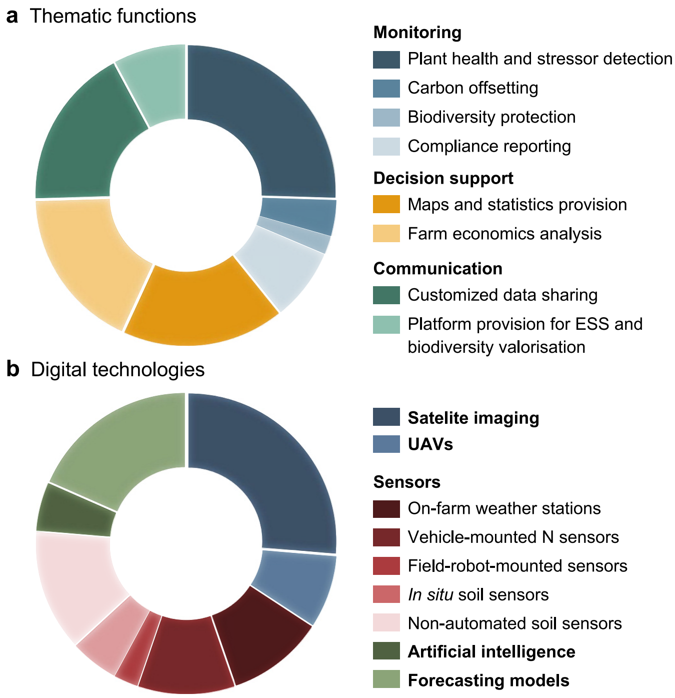

Fig. 3. Numbers of tools supporting different functions (**a**) and digital technologies (**b**) among the shortlist of reviewed digital agriculture tools. The different categories are not mutually exclusive, since one tool may be supporting several functions or employing several digital technologies.

of production optimization.

The function of supporting communication and collaboration between farmers and other societal actors to meet societal demands on biodiversity and ESS is clearly less well represented in most tools compared to the other two functions, yet interesting first endeavours are identified. Many tools explicitly state that they employ customized data-sharing options, e.g., with farm advisors that additionally support farmers' decision-making for production optimization. A handful of tools facilitate communication and enable collaboration between farmers and other actors by providing a platform to valorise climate or environmental-friendly farming practices (e.g., buying carbon offset credits, financially rewarding ESS provision) or promoting partnerships between different value chain levels to meet environmental and economic sustainability standards.

3.3. The DAKIS structure and components

3.3.1. Overview of the DAKIS

Overall, our review indicates that existing digital agriculture tools focus primarily on yield indicators to increase farm-level productivity levels. Monitoring technologies are commonly used to optimize production and streamline farm-level operational management. However, at present, the current DSS landscape does not capitalize on the environmental enhancement and social transformation potential of technological innovation.

A central contribution of the DAKIS is its built-in focus on linking science, strategic decision-making, and farm management support and on facilitating sustainability-oriented strategic planning at broad scales. The DAKIS will complement existing tools through a broader approach, supporting the provision of a range of ESS that include but are not limited to yield productivity. Using the DAKIS, farmers can receive concrete suggestions on land use and management decisions and the associated impacts while considering ESS and biodiversity, as well as system specificities and effects across spatiotemporal scales. Further, considering demand for ESS and biodiversity will foster the collaboration between farmers and open communication pathways with other stakeholders.

To deliver knowledge-based decision support across these different levels, the DAKIS bundles a diverse set of components (Fig. 4). Remote and *in situ* sensing technology monitors indicators for yield productivity and environmental health in high spatiotemporal resolution (Section 3.3.3). Areas with high ESS and biodiversity potentials are mapped via Geographic Information System (GIS) approaches, while an AI expert system is used to identify combinations of land use and management that provide synergies in the delivery of different ESS and biodiversity (Section 3.3.3). In the next step, these combinations are evaluated via modelling in terms of their production, environmental, economic, and social viability effects (Section 3.3.4). Participatory Sustainability Impact Assessment (SIA) addresses societal preferences on the adoption of different management options, as well as environmental and social responses to systemic changes in the agri-food system (e.g., rebound effects of digitalized technology adoption, appreciation of the agricultural sector) (Section 3.3.5).

In the final step, the modelling and the SIA results flow into the DAKIS decision options generator, which integrates outputs of the various components into one common output of the overall system that is consistent, conflict-free, and comprehensible. This consists of spatially-explicit land use and management suggestions that, in accordance with the farmer's specific objectives, reduce trade-offs in the delivery of ESS and biodiversity, economic performance, and achievement of long-term and higher-level sustainability via multi-criteria decision-making algorithms. The system allows the internal inspection of the ranked decision option, i.e., not only gives the user recommendations on what to do, but also provides an explanation of why this recommendation is given, which is of great importance for the user acceptance of the DAKIS.

3.3.2. Interaction with the users and other tools

The DAKIS encourages an interactive process with users and stakeholders to determine land use and management suggestions. Farmers can set farm operation preferences (e.g., technical and management aspects, risks or long-term investments) and specify their objectives regarding the delivery of different ESS and biodiversity aspects. Stakeholders and civil society actors can express ESS and biodiversity demands via spatially explicit and real-time mapping, which can optionally be considered through the DAKIS' decision-making process (Section 3.3.3). Stakeholders can also provide input on the wider impacts of digitalisation on key sustainability criteria, which informs the decision-making component and ensures social viability in future iterations (Section 3.3.5).

A range of scenarios allows for exploring the impact of diverse drivers and uncertainties affecting agricultural systems. These fulfil the dual purpose of broadening farmers' perspective and preparing them for future, digitalisation-induced, systemic changes to their operations, as well as informing other stakeholders about the wider sustainability implications of farm management decisions taken within DAKIS. The scenarios explore the role of changes in prices and policies, evaluate the potential of cooperative solutions, address the degree of societal appreciation of ESS and biodiversity, and capture fundamental shifts in current agri-food systems in terms of the use of digital technologies, producer-consumer interactions, and value chain design (see also Section 3.3.5). These scenarios are pre-run in the DAKIS system and available to be explored by the user.

For farm-specific management support, we develop an open interface that connects the DAKIS to external services such as Farm Management and Information Systems (FMIS). An application

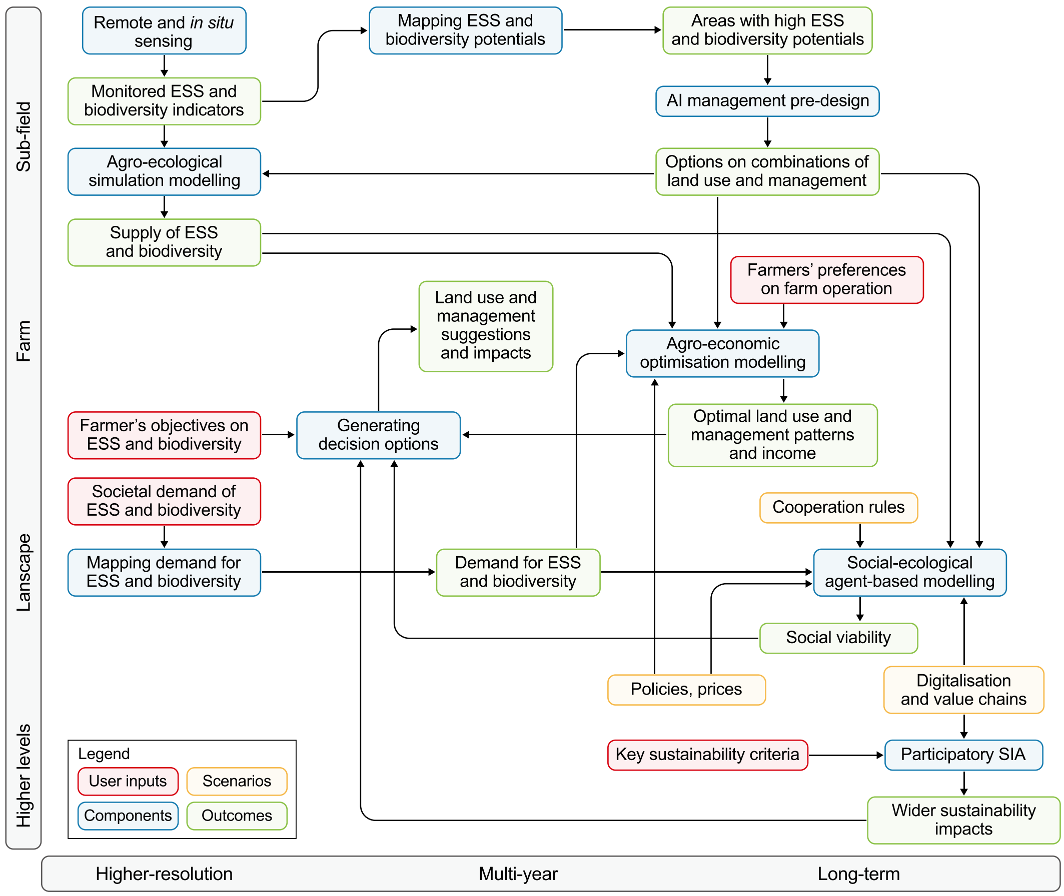

Fig. 4. Overview of the DAKIS user inputs, components, scenarios, and generated outcomes and their respective spatial and temporal formats.

programming interface (API) permits inter-system communication, where DAKIS decision support maps with site-specific recommendations on measure implementation can be imported and processed by an FMIS to create application maps and further distribute information to (autonomous) machines for measure implementation on the field. Through the API, the implementation status of the measure is sent to the DAKIS system to complement the data flow. The approach increases the applicability of the DAKIS in practice, facilitates compliance with documentation standards and regulations, improves the DAKIS models with precise land use and management data (e.g., soil management information), and prevents manual data entry into the system via automated data exchange.

3.3.3. *Sensing, mapping, and AI components*

In the DAKIS, satellite imaging, UAVs, and soil, meteorological and bioacoustic sensors (e.g., for bird or bat species monitoring) are employed to monitor on-farm performance, for instance, crop growth (e.g., leaf area index, normalized difference vegetation index), production conditions (e.g., soil moisture and structure), and ESS and biodiversity indicators (e.g., the cooling effect of landscape arrangements, identification of high nature value grassland). The collection of high spatiotemporal resolution monitoring data allows DAKIS users to assess the current on-farm status and identify priorities and site-specific hotspots for improving the ESS and biodiversity provision. On the one hand, they are displayed as standalone monitoring outputs on the DAKIS Graphical User Interface (GUI), and on the other hand, they constitute the input for further site-specific ESS and biodiversity assessments. Specifically, they are processed using GIS analysis into sub-field or field level maps identifying high potential areas for delivering ESS and biodiversity under improved land use and management changes (see also SM Section 2.3.1 for further details on the mapping of ESS and biodiversity potentials). Currently, the mapping focuses on yield, erosion control, and floristic biodiversity potentials, while in the longer term, the frame will be extended to other ESSs and faunistic biodiversity.

Mapping outputs then feed into a rule-based AI expert system together with rules derived from expert knowledge in order to identify spatially explicit combinations of land use and management that maximize synergies in the delivery of a diverse set of ESS and biodiversity. The inference system is based on an adapted implementation of the RETE pattern-matching algorithm [40], which uses static and dynamic data (e.g., current weather) to reflect given facts that hold true at a given moment as well as formalised rules in a simple “if-then” format which the system uses to derive new facts. An advantage of the approach is that the number of rules and their nested definition are not limited. This allows us to model complex interrelations in an easy and user-friendly way, formalize expert knowledge explicitly, and update, extend or revoke facts and rules. The rules define the planned action, the representation of knowledge of the environment, and the connection to geometric data for plan execution. For example, if we consider the case of planting hedgerows, the rules include definitions and categories of hedgerows, legal regulations, environmental parameters determining hedgerow establishment, etc.

In addition to mapping ESS and biodiversity potentials, mapping the demands of multiple stakeholders for ESS and biodiversity at a landscape scale represents one of the core thematic scopes of the DAKIS that the StABs have evoked. Linking explicitly stated demands to space, we apply a participatory GIS approach where interested stakeholders can specify their demand for ESS and biodiversity in a spatially explicit manner. An example of the approach can be seen in Refs. [41,42]; who asked participants from several stakeholder groups to specify their area of demand and perceived supply of ESS in case study areas shown to them in an online map-based survey tool (https://maptionnaire.com/). These demands are mapped in the DAKIS GUI and can be taken into account by the social-ecological and agro-economic modelling components presented in Section 3.3.4.

3.3.4. Modelling components

To quantify impacts on crop growth, ESS, and biodiversity, the DAKIS models agro-ecological systems via the SIMPLACE (Scientific Impact assessment and Modelling Platform for Advanced Crop and Ecosystem management) modelling framework [43]; www.simplace.net) and two newly-developed stand-alone models on microclimate [44,45] and biodiversity (see SM Section 2.3.2 for details on the agro-ecological modelling components). The SIMPLACE framework captures numerous processes affecting biomass production, crop yield and nutrient content of a large range of crops, selected ESS like groundwater recharge, nitrate leaching, soil carbon sequestration, and GHG emissions in cropland and grassland systems. The microclimate model explicitly simulates the cooling effect of trees and hedgerows on the surrounding landscape under hot summer conditions. The biodiversity model employs a combination of methods for modelling species occurrence and distribution, such as generalized linear mixed-effect models, machine learning techniques and Bayesian networks. Model outputs flow into an agro-economic and a social-ecological agent-based modelling component and inform each component's respective optimization and simulation processes.

The agro-economic modelling component is based on the mathematical farm-level optimization bio-economic model MODAM (Multi-Objective Decision support tool for Agroecosystem Management) [46], which determines optimal land use, management, and investment decisions and quantifies associated income indicators (SM Section 2.3.3 provides further info on MODAM). Bio-economic farm models are often used in science but less often in advising farmers [47]. In DAKIS, we employ this type of modelling to support farmers in their decision-making towards optimal resource allocation in producing commodities while taking into account other ESS and biodiversity. We can run MODAM in two modes. In the farmer-decision support mode, MODAM offers farmers an individual production plan with detailed analyses of risks for different production and investment options, taking into account yield and market risks, shadow values of ESS and biodiversity, and potential compensation payments. Farmers can then change individual settings regarding inputs and preferences to finally obtain a production and business plan that fits their resources and preferences. In the policy support mode, the model runs a number of typical farms to assess the impact of new technologies or a range of policy scenarios at a regional level. Results for different scenarios and trade-offs between different policy objectives or private and public goods can be generated as input to discussions on new instruments or regulations.

For the modelling of social-ecological systems, we employ the ViSA (Viability of Socio-ecological Agroecosystem) agent-based model [48,49] to consider effects on social viability (see SM Section 2.3.4. for further information on the ViSA model). The ViSA model expands the functionalities of the DAKIS spatially and in terms of represented actors. After integrating the demands for ESS specified by several stakeholder groups, including farmers, foresters, policy makers, researchers, nature protection, civil society and associations into ViSA (Section 3.3.3), we run simulations at a sub-district scale for a sequence of years (typically ~10 years). This way, we identify the initial supply-demand gap and simulate the impact of different management options under different decision behaviour of the interacting actors on minimizing this gap. The aim is to raise awareness of farmers on demand for ESS by other actors on their farms or in neighbouring farms and to evaluate the consequences on the social viability of agro-ecosystems under specific land use patterns, management options, cooperation rules, and scenarios on the digitalisation of agriculture. Social viability is represented by the mismatch between the supply and demand for ESS and biodiversity, the associated risk of conflicts between actors, and the evolution of the capitals of the involved actors representing various monetary and non-monetary assets (financial, natural, social, physical, human, and cultural capitals, see Refs. [50,51]. By considering different types of capital, the model considers decision preferences other than profit maximization, reflecting evidence that farmers' actions are also affected by socio-psychological non-financial factors in addition to the financial ones [52].

3.3.5. Participatory SIA

Underpinning the development of SIA in the DAKIS is a stakeholder-inclusive participatory approach based on Bayesian Belief Networks (BBNs). To construct the BBNs, we use a generalized protocol [53] to engage stakeholders, including farmers, civil society organizations, public administrators, and researchers, in interactive workshops. We use the resulting BBNs to develop the SIA by identifying region-specific impact areas and estimating magnitudes of impacts in terms of probabilities. The customizable selection and relative weighting of impact areas (i.e., key factors of sustainability) at the farm, landscape, and global (SDGs) levels, as well as the comparison of trade-offs between impact areas across multiple scenarios, see for example Mitter et al. Dönitz et al., and Hamidov et al. [54–56], are a core functionality. These scenarios outline variations of the adoption of digitalized decisions supported by farmers and the degree of societal appreciation of ESS and biodiversity. Besides modelling the wider impacts of digitalisation on the farming and agri-food system, the BBNs are used to assess the sustainability impacts of specific management options (e.g., hedgerows and agroforestry) being implemented in the DAKIS use cases. This way, they can elicit inputs into the decision-making component of the DAKIS, encouraging social viability.

3.4. The DAKIS use case and GUI

To illustrate the operation of the DAKIS, we adopted a use-case approach focusing on identifying potential hotspots for grassland buffer establishment at the sub-field level. Grassland buffers are landscape elements associated with the delivery of multiple ESS. Here, we focus on their potential to simultaneously maintain yield production while enhancing soil erosion control. In the future, additional ESS (e.g., carbon sequestration potentials, habitat creation for pollinator species, etc.) will be added to this analysis. Our use case is based on a 46-ha site in the Brandenburg test region (Fig. 5, see also Fig. S1 for sketches from the DAKIS GUI on the area).

The steps in the implementation of the use case, serving as an example of how the DAKIS can be used in practice, are the following:

1. To examine the variability of within-field ESS potentials, we subdivide the site into 64 rectangular sub-patches of 0.5 ha. These are parallel to the permanent traffic lane with an edge

length of a multiple of the maximum working width. First, we assess yield production potentials across these sub-patches using real multi-annual yield maps and a fuzzy k-means clustering algorithm [57]. We then apply an erosion hotspot analysis, using site-specific remote sensing data, to the same area to assess erosion control potentials at the sub-patch level. Both datasets are integrated to quantify varying yield and erosion control potentials across sub-patches.

2. We then formulate the central underlying assumption that to minimize trade-offs between yield production and erosion control, grassland buffer establishment should be prioritized on sites with low yield potential and high erosion control potential. Based on this assumption, the RETE reasoner performs a location selection process to identify in which sub-patches grassland buffer implementation may minimize trade-offs and optimize synergies.
3. Once optimal locations for grassland buffer establishment are generated, this spatially-explicit input feeds into the agro-ecological and agro-economic models. The agro-ecological modelling components generate outcomes on ESS (e.g., crop biomass, crop yields, crop N uptake) and biodiversity under two possible land-use options: current land-use versus established grassland buffer patches. The MODAM model then integrates these results and optimizes outcomes by selecting the optimal grass and crop types for each sub-patch.
4. The ViSA model, taking into account societal demands for biomass, erosion control and biodiversity, evaluates the difference in the potential for cooperation and risk of conflict in a case where grassland buffers are established in the proposed locations.

Eventually, the GUI displays to the farmer the areas with high ESS and biodiversity potential, the societal demands for ESS and biodiversity, as well as sustainability impacts at different levels (see Figs. S2−S4 for sketches of the DAKIS GUI). Finally, it provides core output recommendations on the location and management of grassland buffer patches as maps and qualitative information. These recommendations are, on the one hand, economically optimal and, on the other hand, take into consideration the preferences of farmers and the prioritization of their objectives on erosion control, biodiversity, and collaboration against gross margins. Subsequently, the DAKIS GUI, as the systems' front-end, provides the interface that connects the DAKIS to other systems, such as FMIS. In the case of our use case example, the DAKIS application can provide output recommendations on the location and management of grassland buffer patches, displayed in the GUI and importable to FMIS on demand to display and further process the DAKIS recommendations. FMIS outputs, on the other hand, can be delivered back to the DAKIS.

4. Discussion

4.1. Limitations of the literature review approach

Digital agriculture tools rapidly change and adapt to the latest technical and user requirements. Additionally, while in the early implementation stages, several promising digital tools cover specified thematic or spatiotemporal scopes but have the capacity or intention to scale up later. This implies that the results of this review can be quickly outdated. Furthermore, as information on certain tool features and characteristics is not always provided explicitly in the reviewed documentation, the description of the reviewed tools may be incomplete, particularly concerning some of the more detailed features (e.g., types of models and algorithms, sustainability dynamics and scales).

Finally, the selection criteria for tools to be reviewed in more detail are based on allowing better comparability to the DAKIS and its particular novelty. This limits the number of tools for the in-depth analysis to those that embark on a broader consideration of different functions and integrate different digital technologies. Eventually, by this tight selection process (Section 2.2, Fig. 1), tools with comparable functionalities within specific domains and thematic scopes (e.g., focusing only on livestock farming or horticulture) or tools focusing on only one function were excluded by the review. We acknowledge that many other tools employ valuable approaches in various contexts, featuring several technological innovations or technical components that can be adapted to different agricultural domains, e.g., research by Gutiérrez et al. [58]. Although our approach limits the presentation of such features, the finding that existing tools are limited in simultaneously considering ESS and biodiversity, fostering communication and cooperation, and linking multiple spatiotemporal scales and sustainability levels remains valid.

4.2. User relevance of the DAKIS

Reviews of existing DSS identify a “gap of relevance” which often exists between the developers and the desired end-users of such tools, which was also confirmed during consultation workshops with stakeholders. This disconnect constitutes a fundamental challenge to the real-world applicability of digital agriculture tools. The underlying drivers are related to methodological and technical challenges that arise from distilling complex information streams into simple and user-friendly interfaces [6,24,25,31], a lack of understanding regarding end-users' needs, perceptions, and decision-making processes [31,59], insufficient spatial relevance, and limited tool longevity and provision of long-term planning support [6,24,25].

To address these challenges, the DAKIS is built with strong consideration of user experience and stakeholder involvement. By engaging stakeholders on a regular basis and drawing on their knowledge, we can better formulate intended and unintended impacts, foster collaborative learning [60], and ensure a practical and target-oriented development of the thematic relevance of the DAKIS and a user-oriented GUI. To tackle the need for thematic relevance and breadth, the DAKIS facilitates data integration for a broad spectrum of indicators covering locally-relevant production, environmental, economic, and socio-cultural aspects. It generates recommendations based on a systemic trade-off analysis for these indicators, coupled with the site- farm- or region-specific prioritization rules, and facilitates both short- and long-term planning periods. In addition, applying behavioural and preference models and integrating societal demands with farmers' preferences contribute to increased societal relevance and acceptance. The different DAKIS components of innovative digital technologies and models are developed and tested in real-life environments represented by the two project test cases. To further encourage co-creation with the users, the DAKIS will be tested in participatory projects with stakeholders via a living lab for sustainable agricultural landscapes. This will serve as a space for joint research between science and practice to solve real-world and socially relevant sustainability problems while integrating farmers' needs and practical feasibility.

4.3. Opportunities and challenges of digital agriculture

DAKIS attempts to simultaneously address challenges while drawing on opportunities in digital agriculture. Increased availability of digital data constitutes a significant opportunity for the agricultural sector, and digitalisation efforts are likely to benefit

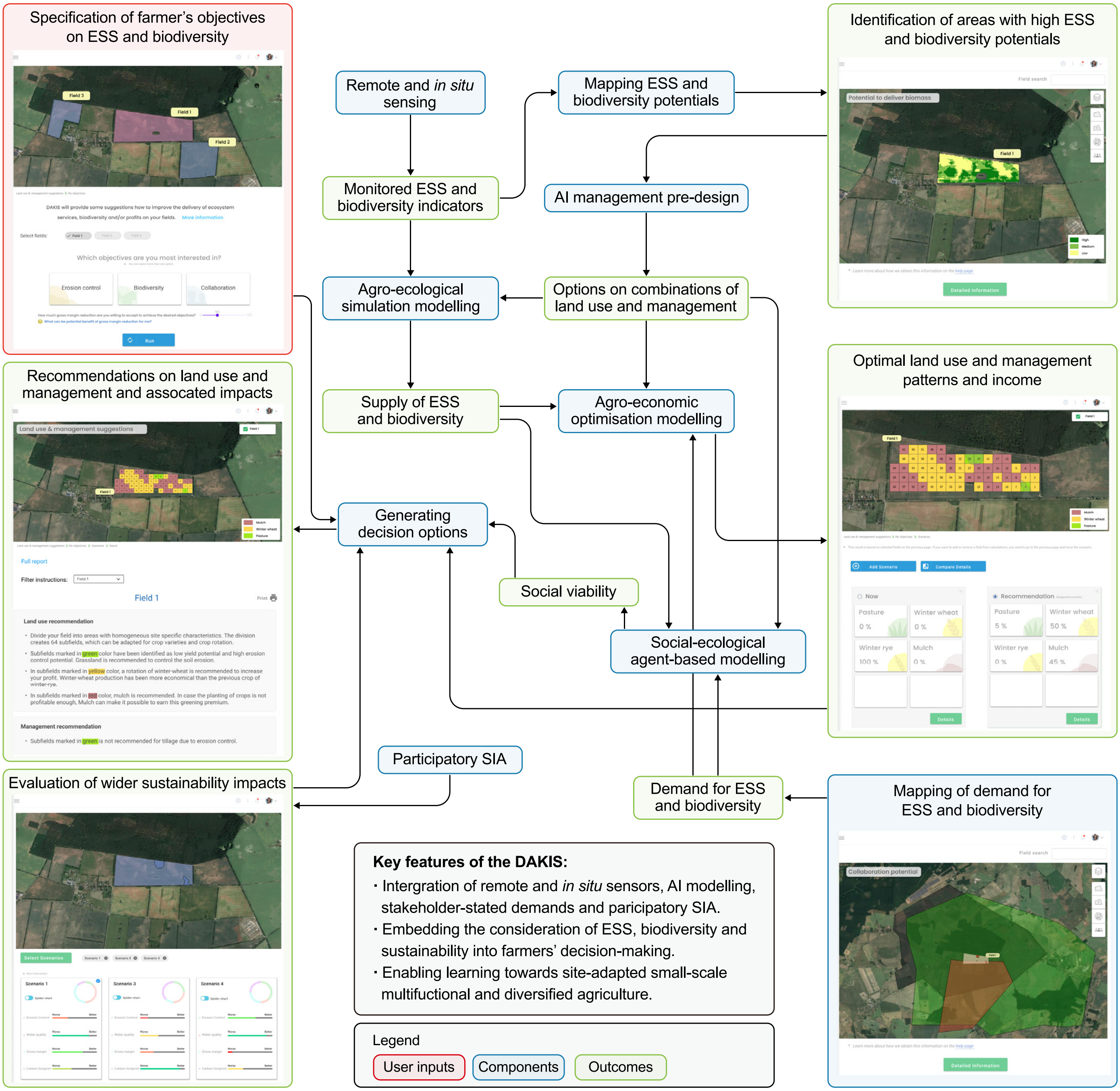

Fig. 5. Overview of the DAKIS features and components as presented in the DAKIS GUI. The sketches are shown with a higher resolution in Figs. S1–S4.

from rapid technical improvements in sensing [61,62], modelling, and robotics and automation [63]. However, the innovative potential of "agriculture 4.0" goes beyond the optimization of agro-technological processes or the replication of current systems in which manual processes are replaced with digital ones. Rather, and more importantly, the transformative potential of digital tools lies in the development of new connection pathways that facilitate information transfer among machines and humans [64], leading to enhanced decision-support and more transparent and sustainably managed agricultural production. Models are advanced and complemented with other approaches to overcome observed limitations in representing social sustainability and multi-functionality [65]. The DAKIS adopts a future-oriented vision in which ESS and biodiversity are established as concrete management goals, which can be monitored and managed using digital tools.

Nevertheless, it is acknowledged that despite the innovation potential of increased reliance on digital data connections, this is also associated with significant socio-economic and environmental risks [11,12,66], data privacy and security questions [67], and the need to address potential data storage issues related to the high digital footprint associated with increased data streams from digital sensors and cameras [68]. Through the inclusion of a foresight study and legal aspects embedded in DAKIS, potential associated risks (e.g., driven by new technology and digitalisation) are identified and conveyed [69].

4.4. Future uptake of the DAKIS

In a perfect world, the demand placed by society on the provision of ESS and biodiversity would be satisfied by farmers with the help of the DAKIS. However, in reality, although the principles and tools presented here have great potential to support sustainable agricultural transformation and a move towards site-relevant and adaptive agro-ecological management solutions, implementing such approaches at scale requires strong buy-in not only from individual farm-level stakeholders but also from industry and policy players [9,70]; Ehlers et al., 2022). Such developments involve systemic changes to farming and agri-food systems, e.g., to open new avenues of producer-consumer interaction and value chain design [69] and to structurally address data privacy or data storage concerns [67,68]. The use of digitalisation to support novel designs of policy instruments which offer more targeted support for sustainability and enhance the benefits of farming [70] is also relevant in this transition.

However, the vision of multifunctional and diversified agriculture can only get adopted if it represents a viable economic alternative to the prevailing agricultural systems. The lack of sufficient economic incentives to encourage the provision of ESS and biodiversity in farming [71,72] can be addressed by targeted policy instruments (e.g., EU Common Agricultural Policy eco-schemes) or by encouraging private partnerships between farmers and individuals or companies via internet-based marketplaces for ESS and biodiversity (e.g., www.agora-natura.de). The DAKIS can assess how current and future payment schemes for biodiversity and ESS affect optimal land use and management decisions and, consequently, the resulting provision of biodiversity and ESS. This can strengthen farmers' motivation to achieve biodiversity and ESS targets by demonstrating economically optimal ways to reach these targets and flexibly testing the impacts of different schemes, eventually mitigating underlying uncertainty associated with the value of biodiversity and ESS. Hence, while public and market-based economic instruments for the valorisation of ESS and biodiversity are expanding [73], the DAKIS, as a system or as a model component supplier, can serve as a solution to quantify the demanded and supplied services under different public or private schemes, as well as to connect their producers and consumers.

Besides its potential as a tool for farmers, the strength of the DAKIS as a tool to facilitate ESS and biodiversity provision in agriculture via other users and in a policy context should be further investigated. Farm advisors can actively support overcoming trade-offs and maximize synergies in the farm, but also landscape and regional planning contexts. From a practical perspective, this would also facilitate immersing into the complexity of the DAKIS system and its implications for farm management and reducing potential technical, financial, administrative or knowledge barriers to farmers themselves. Ultimately, the DAKIS proposes a novel framework through which digital agriculture may be harnessed to facilitate current farm management processes and transform the way farm actors use and integrate multiple flows of information about farming landscapes. To align tool development with this future vision, the DAKIS proposes an adaptable framework structure to manage complex data connections where the range of included datasets and land management options can easily be extended based on end-user targets, related information needs and data availability.

5. Conclusions

Tremendous progress has been achieved in the last decade towards the advancement of digital technologies, and a range of options exists to fulfil an equally broad range of functions and serve diverse purposes. Reviews of existing tools point towards broadly recurring challenges and limitations in the design and uptake of digital DSS for agricultural systems, particularly with respect to ESS and biodiversity integration, the capacity to foster communication and cooperation between farmers and other actors, and the ability to link multiple spatiotemporal scales and broader sustainability levels.

To address these challenges, the DAKIS builds on existing research and lessons learned and is based on a well-defined requirement structure, which was developed upon participatory and iterative processes. A principal novelty of the DAKIS is that it uses digital technologies to render possible the consideration of ESS, biodiversity, and sustainability into farmers' decision-making, providing a DSS through which farmers are informed and guided towards site-adapted small-scale multifunctional and diversified agriculture along self-defined avenues. To achieve this, it bundles and analyses a wide range of static and dynamic data from various sources delivered to the user via an interconnected spatiotemporally explicit approach, which assimilates the diverse drivers affecting agricultural land use and management design, including natural and agronomic factors, economic and policy considerations, and socio-cultural preferences and settings. To encourage long-term participation and adoption of the DAKIS by important stakeholders, it maintains the scale-relevance of its outputs at the sub-field and farm level while offering a learning system for an inclusive stakeholder exchange on sustainable development objectives.

CRediT authorship contribution statement

Ioanna Mouratiadou: Conceptualisation, Methodology, Investigation, Writing - Original draft, Visualization, Supervision, Project administration. **Nahleen Lemke**: Conceptualisation, Methodology, Investigation, Writing - Original draft, Visualization, Project administration. **Cheng Chen**: Methodology, Writing - Original draft, Visualization, Project administration. **Ariani Wartenberg**: Writing - Original draft, Visualization. **Ralf Bloch**: Conceptualisation, Supervision, Project administration, Funding acquisition. **Marco Donat**: Methodology, Writing - Review & Editing. **Thomas Gaiser**: Conceptualisation, Methodology, Writing - Review & Editing, Supervision, Funding acquisition. **Deepak Hanike Basavegowdae**: Methodology, Writing - Review & Editing. **Katharina Helming**: Conceptualisation, Methodology, Writing - Review & Editing, Supervision, Funding acquisition. **Seyed Ali Hosseini Yekani**: Methodology, Writing - Review & Editing. **Marcos Krull**: Methodology, Writing - Review & Editing. **Kai Lingemann**: Conceptualisation, Methodology, Writing - Review & Editing, Supervision, Funding acquisition. **Joseph Macpherson**: Methodology, Writing - Review & Editing. **Marvin Melzer**: Methodology, Writing - Review & Editing. **Claas Nendel**: Conceptualisation, Methodology, Writing - Review & Editing, Supervision, Funding acquisition. **Annette Piorr**: Conceptualisation, Methodology, Writing - Review & Editing, Supervision, Funding acquisition. **Mostafa Shaaban**: Methodology, Writing - Review & Editing. **Peter Zander**: Conceptualisation, Methodology, Writing - Review & Editing, Supervision, Funding acquisition. **Cornelia Weltzien**: Conceptualisation, Supervision, Funding acquisition. **Sonoko Dorothea Bellingrath-Kimura**: Conceptualisation, Methodology, Writing - Original draft, Supervision, Project administration, 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.

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Appendix A. Supplementary data

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