Supplementary material to the manuscript

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

Ioanna Mouratiadou[1,2], Nahleen Lemke[1], Cheng Chen[1], Ariani Wartenberg[1], Ralf Bloch[3], Marco Donat[1], Thomas Gaiser[4], Deepak Hanike Basavegowda[5], Katharina Helming[1,3], Seyed Ali Hosseini Yekani[1], Marcos Krull[1], Kai Lingemann[6], Joseph Macpherson[1], Marvin Melzer[1], Claas Nendel[1,7,8], Annette Piorr[1], Mostafa Shaaban[1], Peter Zander[1], Cornelia Weltzien[5], Sonoko Dorothea Bellingrath-Kimura[1]*

[1] Leibniz Centre for Agricultural Landscape Research (ZALF), Eberswalder Straße 84, 15374 Müncheberg, Germany

[2] ISARA, Laboratory of Rural Studies research unit, Lyon, 23 rue Jean Baldassini, 69364 Lyon cedex 07, France

[3] Faculty of Landscape Management and Nature Conservation, University for Sustainable Development (HNEE), Schickler Straße 5, 16225 Eberswalde, Germany

[4] Institute of Crop Science and Resource Conservation, University of Bonn, 53115 Bonn, Germany

[5] Leibniz Institute for Agricultural Engineering and Bioeconomy (ATB), Max-Eyth-Allee 100, 14469 Potsdam, Germany

[6] German Research Center for Artificial Intelligence (DFKI), Trippstadter Strasse 122, 67663 Kaiserslautern, Germany

[7] Institute of Biochemistry and Biology, University of Potsdam, Am Mühlenberg 3, 14476 Potsdam (Golm), Germany

[8] Global Change Research Institute, The Czech Academy of Science, Bělidla 986/4a, 603 00 Brno, Czech Republic

*Corresponding author: imouratiadou@isara.fr

1 Materials and methods

Table S1. Outline of meetings and workshops (WSs) with stakeholders in chronological order.

Date	Meeting	Participants	Aim of the meeting	Short description
27-28/09/2017	Foresight WS	DAKIS project consortium, farmer, representative of commercial digital tool supplier (365FarmNet)	Joint vision creation.	The DAKIS project consortium formulated a joint vision for the DAKIS. The participation of a farmer and a representative of the company 365FarmNet allowed capturing insights from a practical farm management perspective.
16/11/2017	Stakeholder WS Brandenburg	Regional stakeholders from the agricultural sector (practice, consultation), researchers, farmers' associations, nature conservation organization, policy makers	Presentation of the DAKIS, critical discussion and further vision development.	Critical discussion of the DAKIS vision, where stakeholders addressed opportunities and challenges related to the vision.
28/11/2017	Stakeholder WS North Rhine-Westphalia			
06/12/2017	Stakeholder WS Bavaria			
23/06/2020	Stakeholder Advisory Board (StAB) meeting Bavaria	Bavaria StAB	Feedback on the DAKIS aims, functions and overall development, as well as the possibility to connect to other digitalization approaches and agro-environmental measures.	Presentation of the current DAKIS DSS aims, scales, functionality and components, followed by an intensive feedback and discussion round. Practitioner's feedback on DSS functionalities and the critical reflection of those requirements developed within the project endorsed new perspectives for further development.
26/06/2020	StAB meeting Brandenburg	Brandenburg StAB		
08/06/2021	StAB meeting Bavaria	Bavaria StAB	Feedback on the DAKIS architecture and Graphical User Interface (GUI). Presentation of current results of ecosystem services (ESS) assessment (erosion control). Workshop about agricultural measures and sustainability regarding presented GUI and assessment results.	Presentation of progress in terms of including previous StAB feedback into the DAKIS, as well as a first presentation of the GUI via a clickable demo version. Discussion concerning the practicability and user friendliness, but most importantly the tools functions, and options for their integration.
10/06/2021	StAB meeting Brandenburg	Brandenburg StAB		

Table S2. Outline of internal meetings and WSs with consortium members in chronological order.

Date	Meeting	Aim of the meeting
14.06.2019	WS "Conception of the DAKIS system"	Discussion on the aims of the DAKIS and approaches to encourage the use of the tool by the aimed users.
14.06.2019	WS "Sensing, Monitoring, Implementation"	Exchange on the technologies to be used and the timing and protocols of the monitoring campaigns.
14.06.2019	WS "Stakeholder involvement and foresight"	Alignment and design of the different stakeholder activities undertaken within the project and discussion on the use of generated outcomes within the DAKIS.
12-14.05.2020	WS "Farm model"	Discussion on the use of the farm model within the overall decision-making process of the DAKIS and links to other components.
12-14.05.2020	WS "Sustainability assessment"	Identification of key sustainability criteria and indicators to be reflected in the DAKIS.
12-14.05.2020	WS "DAKIS Decision Support System"	Presentation of ideas on the DAKIS aims, scales, functionality and components. Converging towards a common vision and process for developing the DAKIS.
12-14.05.2020	WS "Task Forces"	Development of cross-work package task forces to steer result integration to DAKIS prototype.
03.09.2020	WS "The concept of the DAKIS "	Presentation of current concept version of the DAKIS and feedback from stakeholder advisory boards (StABs). Discussion of component interfaces and further development.
03.09.2020	WS "Prototype Database"	Presentation of the technical architecture of the DAKIS and associated database.
04.09.2020	WS "Management Task Force"	Integration of land management sub themes to create management rules for combining land uses, land classes and management (including different levels of intensity).
04.09.2020	WS "Scenarios and Vision"	Synchronization of requirements and wishes regarding the DAKIS architecture and functions with four scenarios.
21.01.2021	Meeting on "DAKIS Prototype: status update and plans"	Update on the current state of the DAKIS prototype (frontend and backend, its aims and open discussion on its way forward.
20.05.2021	WS "Scenario integration to the Agent Based Model"	Establishment of an approach for scenario assessment in the agent-based model.
26.05.2021	WS "Prototype development of the Graphical User Interface (GUI)"	Development of suggestions and concretization of the DAKIS GUI functions and its design.
26.05.2021	WS "Prototype rules and optimization"	Collection and discussion of rules defining how various data and information from different work packages should be combined and integrated into the DSS.

Table S3. Members of the DAKIS StABs.

Profession/Function	Affiliation
Bavaria StAB	
Farmer	Mayerhofer Agrar, Blogger
Advisor	German Landcare Association (DVL)
Advisor	Bavarian Farmers' Association
Advisor	Bioland
Advisor	Bavarian Farmers' Association
Farm Management Information Systems developer	Geflügelhof Pauli, Farmfacts Software
Political consultant	State Institute for Agriculture
Political consultant	Office of Food Agriculture and Forestry Passau-Rotthalmünster
Political consultant	Bavarian State Ministry of Food, Agriculture and Forestry (StMELF)
Brandenburg StAB	
Farmer	Schlossgut Alt Madlitz
Farmer	Gut Wilmersdorf
Farmer	Müncheberger Agrargesellschaft
Advisor	German Landcare Association (DVL)
Scientist	Fraunhofer Institute, Automotive and Commercial Vehicles and Business Development
Scientist	Helmholtz Centre for Environmental Research (UFZ), Head of Department Soil System Science
Scientist	Technical University Dresden, Institute for Natural Material Technology and Agricultural Systems and Technology
Political consultant	Federal Agency for Nature Protection (BfN)
Political consultant	Ministry of Agriculture, Environment and Climate Protection (MLUK) Brandenburg

Table S4. Search strings used for the literature review.

Search engine	Query
Google search	Keywords such as ‘digital agriculture’, ‘farm management system’, ‘digital tools’, ‘digital decision support’, ‘digital and smart farming solutions’, ‘agricultural automation’, ‘digital farming platforms’, ‘information provision’ and ‘information visualisation’ in agriculture, ‘digital resource sharing’ in agriculture. A snowball-method to increase information hits was conducted.
Scopus Science Direct	(TITLE-ABS-KEY (agriculture AND digital AND app* OR application*) AND TITLE-ABS-KEY (smartphone OR tablet OR mobile AND device)) AND PUBYEAR > 1999 AND (EXCLUDE (SUBJAREA , "DENT") OR EXCLUDE (SUBJAREA , "IMMU") OR EXCLUDE (SUBJAREA , "PHAR") OR EXCLUDE (SUBJAREA , "PSYC"))
	TITLE-ABS-KEY (agriculture AND practice OR operation AND digital AND drone* OR aerial AND imagery OR biodiversity) AND PUBYEAR > 1999
	TITLE-ABS-KEY (agriculture AND digital AND farm AND management AND system*) AND PUBYEAR > 1999
	TITLE-ABS-KEY (agriculture AND iot AND sustainability OR biodiversity) AND PUBYEAR > 1999
	TITLE-ABS-KEY (agriculture AND digital AND sensor OR auto* AND data AND upload)
	TITLE-ABS-KEY ((biodivers* OR (divers* W/10 (crop* OR species OR habitat OR genetic))) AND (crop* OR agri*) AND (app* AND (smartphone OR tablet OR (mobile AND device)))) AND PUBYEAR > 1999
	TITLE-ABS-KEY ((biodivers* OR (divers* W/10 (crop* OR species OR habitat OR genetic))) AND (crop* OR agri*) AND (drone* OR (aerial AND image*))) AND PUBYEAR > 1999
	TITLE-ABS-KEY ((biodivers* OR (divers* W/10 (crop* OR species OR habitat OR genetic))) AND (crop* OR agri*) AND (digital AND farm AND management AND system)) AND PUBYEAR > 1999
	TITLE-ABS-KEY ((biodivers* OR (divers* W/10 (crop* OR species OR habitat OR genetic))) AND (crop* OR agri*) AND (iot OR "internet of things")) AND PUBYEAR > 1999
	TITLE-ABS-KEY (biodivers* AND agri* AND digital AND (sensor OR auto*) AND data) AND PUBYEAR > 1999
	TITLE-ABS-KEY ((biodivers* OR (divers* W/10 (crop* OR species OR habitat OR genetic))) AND (crop* OR agri*) AND (sensor* OR sensing OR rs OR gis) AND ((digital OR data) AND (upload Or connect*))) AND PUBYEAR > 1999

2 Results

2.1 Requirements for the DAKIS

Table S5. Outcomes of iterative exchange with stakeholders and consortium members.

<table>
<tr><th>Date</th><th>Meeting</th><th>Outcomes</th></tr>
<tr><td>27-28/09/2017</td><td>Foresight WS</td><td>• Integration of insights from a both practical farm management perspective and research perspectives.
• Identification of individual values and visions concerning agriculture, cooperation and DAKIS and discussion of synthesis and barrier points towards a common vision.
• Development of indicators, milestones and method ideas to implement a joint vision.

Principal Outcome: Formulation of a joint, long-term vision for the DAKIS including sensing and IT-supported software development, ESS, and cooperation enhancement, transparent societal impacts, new production systems and farm operational structures.</td></tr>
<tr><td>16/11/2017</td><td>Stakeholder WS Brandenburg</td><td rowspan="3">• Inclusion of both scientific monitoring and practical monitoring (involving practical support by regional relevant actors) was recognized to be crucial.
• Identification of the need for more prominent valuation of ESS and biodiversity provision in farmers´ decision-making processes, along with linking such efforts to political eligibility through the EU CAP.
• Identification of knowledge transfer systems such as sustainability impact assessment (e.g., SDG reporting) as crucial element to improve transparency among collaborating actors (e.g., farmers as suppliers and consumers).
• Data sovereignty and data security were raised as main concerns to be prioritized with ongoing stakeholder involvement.
• Identification of 2 contrast-rich test regions within Germany to apply the DAKIS concept to.
• Establishment of a DAKIS stakeholder network
• Establishment of project advisory boards in both test regions. The project advisory board consists of representatives from civil society, policy and the regional agricultural sector, who will accompany process development for the duration of the project and ensure compatibility between DAKIS scope and stakeholder visions.

Principal Outcome: Identification of salient risks and opportunities related to the DAKIS joint vision and establishment of a stakeholder network and two project advisory boards.</td></tr>
<tr><td>28/11/2017</td><td>Stakeholder WS North Rhine-Westphalia</td></tr>
<tr><td>06/12/2017</td><td>Stakeholder WS Bavaria</td></tr>
</table>

23/06/2020	StAB meeting Bavaria	• Presentation of current DAKIS DSS aims, scales, functionality and components. • Definition of farmers as the core users of the DAKIS; as a result, decision-making in DAKIS must (i) take into account farmers' needs, preferences, and economic constraints; (ii) issue decision support; and (iii) promote communication between farmers, and with other stakeholders. • Recognition of payment gaps and their role in motivating farmers towards a shift in land use and management to meet ESS and biodiversity demand and potential. • Discussion of application needs ranging from field- to landscape level to facilitate both farm-level management and wider, landscape-level sustainability targets. • Discussion of open interfaces (including technical and administrative components) as essential to a software application, e.g. to link farm practices and use embedded monitoring functions to facilitate result-oriented policy measures. **Principal Outcome: Discussion of current shortcomings of the DSS and formulation of new guiding requirements and recommendations for further project development and implementation.**
26/06/2020	StAB meeting Brandenburg	
08/06/2021	StAB meeting Bavaria	• Evaluation of project progress regarding the inclusion of previous StAB feedback into the DAKIS prototype, and regarding the visualization of the DAKIS GUI and embedded research progress. • Presentation of a first user story as a clickable demo version, based on initial developments of the DAKIS GUI, which included first research results on land potentials for ESS, potentials and monitoring of biodiversity, agro-economic system modelling, the spatially explicit demand for ESS and biodiversity and first insights of the impact assessment integration into DAKIS. • Discussion of different perspectives concerning the practicability and user friendliness. • Exploration of the tools´ functions and integration options. • Identification of the integration of interfaces with other digital tools (FMIS, DP) as a crucial function, to minimize duplication of functionality between existing tools, to streamline data input steps for farmers, and to maintain transparency of underlying DAKIS DSS processes. • Evaluation of the user experience of the GUI formulation of suggestions to sharpen user stories. • Decision to integrate "use cases" into the DAKIS prototype development to test the DAKIS system architecture for congruency, e.g. check for data flow, analysis and modelling as well as representation within the GUI **Principal Outcome: Evaluation of the DAKIS prototype and identification of strategies for improvement.**
10/06/2021	StAB meeting Brandenburg	

2.2 Literature review findings on digital agriculture tools

Table S6. Functions and digital technologies of the commercial (C) and science-based (SB) digital agriculture tools identified via the review screening process.

No	Type	Tool name and reference	Functions			Digital technologies		
			Monitoring	Decision Support	Communi-cation	Remote sensing	In-situ sensing	Artificial intelligence
1	C	**365FarmNet** (365FarmNet, 2021)	√	√	√	√		
2	C	AGRAVIS NetFarming (AGRAVIS Digital GmbH, 2021)	√	√			√	
3	SB	**Agricolus** (Agricolus, 2021)	√	√	√	√	√	
4	C	**Agricon** (Agricon, 2022)	√	√	√		√	
5	C	Agrinavia (Agrinavia, 2022)	√	√		√		
6	SB	Agro 4.0 (da Fonseca et al., 2020)	√	√		√	√	√
7	C	Akkerweb (Akkerweb, 2021)	√	√	√	√	√	
8	C	CLAAS AGROCOM and Precision Farming Software (Claas, 2022)	√	√			√	
9	C	**Conservis/ClimateFieldView** (Climate FieldView, 2020; Conservis, 2021)	√	√	√	√	√	
10	SB	**CropSat** (Lindblom et al., 2017)	√	√		√		
11	C	Crop SRM (Crop SRM, Farmflo, Farm Flo Limited, 2021)			√			
12	C	DELOS (DELOS, 2022)	√	√				
13	C	eFeldkalender (eFeldkalender GmbH, 2022)	√					
14	C	eLMID (ISAGRI GRUPPE. COBERA-Land GmbH, 2022)	√	√				
15	C	Farmdok (Farmdok GmbH, 2021)	√	√				
16	C	**FarmersEdge** (FarmersEdge, 2022)	√	√	√	√	√	√
17	C	FarmInfo (geo-konzept GmbH)	√	√		√	√	
18	SB	**FarmNET** (Zheleva et al., 2017)	√	√		√		
19	C	Farmpilot (Arvato Systems GmbH, 2022)		√				
20	C	FarmServer (FARMserver, 2020)	√	√		√		
21	SB	FieldTouch (Honda et al., 2014)	√	√		√	√	

22	C	Field-TRAKS (FieldTRAKS Solutions Inc, 2019)	√	√			√	
23	C	FIWARE (López-Riquelme et al., 2017)	√					
24	SB	GIS-ELA (Hauer et al., 2019)	√	√		√		
25	C	HELM Software (HELM-Software, 2022)	√					
26	SB	**LandCaRe** (Wenkel et al., 2013)	√	√	√	√		
27	C	MEIN-ACKER | MASCHINENRING (Maschinenringe Deutschland GmbH, 2022)	√					
28	C	mobiler Ackermanager (Stadtmann, 2022)	√					
29	SB	**NaLamKi** (NaLamKi, 2021)	√	√		√	√	√
30	C	**NEXT Farming** (NEXT Farming, 2022)	√	√	√	√	√	
31	SB	NIVA (Kenny and Regan, 2021)	√		√	√	√	√
32	C	Plantivo (Plantivo GmbH, 2022)	√					
33	SB	Plantix (PEAT GmbH c/o Plantix, 2022)	√		√		√	√
34	SB	Ploovium (Soonapse, 2018)	√	√			√	
35	C	**SMAG** (SMAG, 2021)	√	√	√	√	√	
36	C	Smartcloudfarming (SmartCloudFarming, 2021)	√			√	√	√
37	SB	Soil Navigator DSS (Debeljak et al., 2019)	√	√				√
38	C	The Yield - Sensing+ for Agriculture (The Yield AgTech Solutions, 2021)	√				√	√
39	C	top farmplan (LV digital GmbH, 2021)	√					
40	C	**Topcon Agriculture Platform (TAP)** (Topcon Corporation and Topcon Positioning Group, 2019)	√	√	√		√	
41	C	**Trimble Farmer Pro/Advisor Prime** (Trimble Agriculture, Trimble Inc., 2022)	√	√	√	√	√	
42	C	xarvio Digital Farming Solutions (BASF Digital Farming GmbH, 2022)	√	√		√	√	

Note: The highlighted tools are the ones shortlisted for the in-depth review.

Table S7. Digital agriculture tools selected for the in-depth review.

Name	Type	Country of origin	Description
365FarmNet (365FarmNet, 2021)	C	Germany	A software for agricultural businesses, integrating farm business operations in one platform to facilitate workflows and management in the field of arable farming.
Agricolus (Agricolus, 2021)	SB	Italy	An AgriTech platform, affirming environmental and economic sustainability, to simplify and enhance the work of farmers and agricultural operators.
Agricon (Agricon, 2022)	C	Germany	A precision farming tool that aims to facilitate data flow, management, and machinery connection based on supplied technical infrastructure, and a data management system.
Conservis/ClimateFieldView (Climate FieldView, 2020; Conservis, 2021)	C	US	A farm management system with information layers on the operational and financial information of a farm aiming at better understanding and managing an operation.
CropSat (Lindblom et al., 2017)	SB	Sweden	A tool to follow crop development during the season and to control nitrogen (N) applications based on crop needs.
FarmersEdge (FarmersEdge, 2022)	C	Canada	A platform integrating real-time data through farm digitization and device connectivity to bring together productivity/profit optimisation, sustainability, and carbon strategies.
FarmNET (Zheleva et al., 2017)	SB	US	A tool for agricultural smallholder production providing robust control mechanisms for production through sensors, networks, data analytics and autonomous, proactive farming.
LandCaRe (Wenkel et al., 2013)	SB	Germany	"An interactive decision support system for climate change impact assessment and the analysis of potential agricultural land use adaptation strategies."
NaLamKi (NaLamKi, 2021)	SB	Germany	"A cloud-based software-as-a-service platform with open interfaces for providers from the fields of agriculture, industry, and service providers in crop production is to be created."
NEXT Farming (NEXT Farming, 2022)	C	Germany	A platform aiming at easy-to-use applications for optimized agricultural production and management support while considering sustainability aspects.
SMAG (SMAG, 2021)	C	France	A tool aiming at a digital transformation of the agricultural sector to enable economic and environmental farming performance.
Topcon Agriculture Platform (TAP) (Topcon Corporation and Topcon Positioning Group, 2019)	C	US	A platform to connect farm data and improve data visualization, facilitate machinery connection for enhanced precision farming and data management.
Trimble Farmer Pro/Advisor Prime (Trimble Agriculture, Trimble Inc., 2022)	C	US	A tool to facilitate data flow and machinery connection for enhanced precision farming and data management.

Table S8. Thematic scope of the digital agriculture tools reviewed in depth.

Tool	Production	Environmental	Economic	Social
365FarmNet	- Crops - Livestock	- Soil compaction	- Farm stocks based on purchases and sales - Gross income and gross margins based on costs, income expectations, current price levels, sales, contracts and future market positions - Opportunity/risk ratio changes for different marketing strategies	n/a
Agricolus	- Crops	n/a	n/a	n/a
Agricon	- Crops	n/a	n/a	n/a
Conservis / Climate FieldView	- Crops	- Carbon credits	- Farm stocks based on purchases and sales - Operational and financial plans at field-level - Whole-farm budgets (gross-margin and gross-profits) - Expenditures, comparisons to budgets and updates in changing conditions - Cost and profitability analysis at sub-field, field, or farm level - Profitable practices to optimize and control costs - Performance and efficiency across fields, seeds, protectants, and nutrients	n/a
CropSat	- Crops	n/a	n/a	n/a
FarmersEdge	- Crops	- GHG emissions - Air quality - Soil health - Biodiversity - Water quality	- Cost summaries for various operational scenarios, including crop rotations, variety/hybrid selections, chemical applications and other - Analysis of the cost of decisions: equipment, applications, field activities, yields, logistics, profit	n/a
FarmNET	- Crops - Livestock	- Soil health	- Yield and production value	n/a
LandCaRe	- Crops	- GHG emissions - Soil health - Erosion - Water quality - Resource efficiency - Climate - Vegetation ontogenesis	- Yield and production value - Cost-benefit analysis of farm management strategies - Irrigation worthiness	n/a
NaLamKi	- Crops	n/a	n/a	n/a
NEXT Farming	- Crops - Livestock	- Biodiversity - Carbon sequestration - N emissions	- Cost-performance calculation - Profit contribution calculation - Machine cost calculation	n/a

		- Soil nutrient and water balance - Groundwater recharge - Water holding capacity - Erosion risk	- Calculation of costs and revenues for proceedings - Calculation of farm-specific costs and revenues for all resources	
SMAG	- Crops - Livestock	n/a	- Management stock movements, inventories, stock balance sheet - Gross margins, costs and revenues - Farm-specific costs and revenues for all resources	n/a
Topcon Agriculture Platform	- Crops - Livestock	n/a	n/a	n/a
Trimble Farmer Pro/Advisor Prime	- Crops	n/a	n/a	n/a

Table S9. Spatiotemporal scales of the digital agriculture tools reviewed in depth.

	SPATIAL SCALES					**TEMPORAL SCALES**			
	Sub-field	**Field**	**Farm**	**Landscape**	**Higher levels**	**Real-time**	**Yearly**	**Multi-year**	**Long-term**
365FarmNet	√	√	√				√	√	
Agricolus	√	√					√	√	
Agricon	√	√	√				√		
Conservis/ClimateFieldView	√	√	√	√		√	√	√	√
CropSat	√	√					√		
FarmersEdge	√	√	√	√		√	√	√	
FarmNET	√	√	√			√	√		
LandCaRe	√	√	√	√			√		√
NaLamKi	√	√	√			√	√		
NEXT Farming	√	√	√	√			√	√	
SMAG	√	√	√			√	√		√
Topcon Agriculture Platform (TAP)	√	√	√				√		
Trimble Farmer Pro/Advisor Prime	√	√	√				√		

Table S10. Functions of the digital agriculture tools reviewed in depth.

	Monitoring	Decision support	Communication
365FarmNet	- Monitoring production via satellite-based vegetation monitoring and non-automated soil samples - Farm documentation modules	- Crop-specific and site-adapted seeding, model-based optimized fungicide application, pesticide and fertilizer recommendations based on vegetation and yield maps, tyre pressure calculator based on machine, soil conditions and field planner component to optimize machinery routes - Farm economic data (farm stocks, gross income, gross margin, opportunity and risk ratios) considered for decision support on management suggestions	- Customized data sharing with relevant partners
Agricolus	- Monitoring production and threats to production (crop disease, water stress, soil analysis) via satellite imaging and respective vegetation indexes (e.g., Normalized difference vegetation index - NDVI), weather stations, and automated traps	-Forecasting models for crop development and variable rate fertilization	- Customized data sharing with relevant partners - Partnerships with equipment suppliers, agriculture training services, business consultants, co-marketing and research organizations to meet demands of diverse agri-food chain stakeholders and of the market of Agriculture 4.0 - Runs agronomy education academy to teach stakeholders the techniques of smart agriculture
Agricon	- Monitoring of production (N monitoring) with vehicle mounted sensors and non-automated soil samples - Automated digital documentation of applications	- Site adapted fertilizer planning and the creation of site adapted fertilizer and pesticide application maps	- Customized data sharing with relevant partners
Conservis / Climate FieldView	- Monitoring production via satellite images, status reports on implemented activities and applied inputs, non-automated soil samples and historical yield data - Monitoring data as input for carbon credit generation	- Crop-specific and site-adapted seeding, pesticide recommendations and crop stage based fertility planning based on monitoring data - Investment decisions supported by partnership to Rabobank (global food and agriculture bank)	- Customized data sharing with relevant partners - Certification of food production (GMO-free, organic) - By field data and field practice tracking, it generates data to create

	- Necessary field data is stored in the system for purposes of documentation	- Farm economic data (farm stocks, gross margin, gross profits, cost and profitability calculations, performance and efficiency calculations), operational and financial plans considered for decision support on management suggestions	carbon credits that could be used in a context of carbon markets
CropSat	- Monitoring production by vegetation index maps via satellite-imaging	- Creation of variation maps and prescription files for adapted fertilizer application; user instructions for yield map interpretation and for designing variable rate application files based on user specified inputs (mainly N but also e.g., fungicides or growth regulators)	n/a
FarmersEdge	- Monitoring production (crop health, NDVI, variation, scouting) via satellite-based map layers, weather station and soil moisture probes (sensors) - Monitoring data as input for carbon credit generation	- Predictive models to support pest management (scouting accuracy, application timing and threshold identification) and N management tool to optimize N applications using high resolution data - Farm economic data (cost summaries for different operational and management scenarios) considered for decision support on management suggestions	- Customized data sharing with relevant partners - Online platform for carbon credit generation by farmers and allowing societal actors to buy carbon offsetting credits
FarmNET	- Monitoring of production (crop growth and health) and soil conditions enabled by network of Internet of things (IoT) devices providing real time information	- Yield and water mapping and automated operations e.g., tillage, fertilization; model estimation and control of all farm operations to maximize output while minimizing environmental footprint - Farm economic data (yield and production values) considered for decision support on management suggestions	n/a
LandCaRe	- Monitoring of production via land cover data - Data inputs shared by the user	-Model-based output data (maps, diagrams, stats etc.) to adapt to farm- and region-specific land use management (e.g., fertilizer management) within different climate-change scenarios -Farm economic data (yield and production values, cost-benefit analysis), and irrigation worthiness considered for decision support on management suggestions	- Data sharing with advisor, consultant, admin bodies, farmers

NaLamKi	- Monitoring production (phenological state, biomass), as well as detection of disease and soil-water conditions, by combination of satellite imagery, vehicle mounted cameras, inventory history, weather stations, and soil sensor data	- Fertilizer application recommendations with AI modelling, to optimize irrigation, plant protection, and precision pest and fertilization management	- n/a
NEXT Farming	- Monitoring production (crop monitoring and analysis) satellite-based, as well as potential threats to production via non-automated soil sample and weather station-based monitoring of soil moisture and water balance, N sensors, pest trap with daily images (automatic pest identification and counting) and UAV-based imaging for insect (Trichogramma) infestations - Monitoring biodiversity (fawn detection) via UAVs - Field data is stored in the system for purposes of documentation	- Recommendations for site-adapted seeding (maize only), precise fertilizer applications based on the N-management tool, and precise pesticide applications based on application timer tool and forecast modelling - Farm economic data (cost performance, profit contributions, other cost and revenues) considered for decision support on management suggestions	- Regional climate sponsorships where communities, companies and citizens can reward environmental services of "climate farmers" (Initiative Klima-Landwirt)
SMAG	- Monitoring production via satellite or UAV-based imaging and on site-specific data, IoT monitoring connected farm devices (weather stations, sensors, connected insect traps, etc.) - Reporting facilitation for regulation compliance	- Recommendations on precise fertilization and fungicide applications (wheat only) based on monitoring data - Farm economic data (farm stocks, gross margins, other costs and revenues) considered for decision support on management suggestions	- Customized data sharing with relevant partners
Topcon Agriculture Platform (TAP)	- Data inputs shared by the user - Monitoring production (N monitoring) with vehicle mounted sensors and yield monitoring from the provider itself	- A platform-based combination of data inputs and visualization for precise fertilizer and pesticide application recommendations	- Customized data sharing with relevant partners
Trimble Farmer Pro/Advisor Prime	- Monitoring production (crop health) via satellite imaging and calibration algorithm, non-automated soil samples and in-field yield monitoring tool, for optimizing crop species detection - Reporting facilitation for monitoring, management and harvesting activities	- Yield data cleaning tool for precise yield and application maps, site-adapted application recommendations	- Customized data sharing with relevant partners

Table S11. Digital technologies employed by the digital agriculture tools reviewed in depth.

	Remote sensing	In-situ sensing	AI	Modelling
365Farm Net	- Raw data from Sentinel 2 satellites	n/a	n/a	Forecast model for optimized fungicide application, based on daily, site- specific calculation of the risk of plant infection
Agricolus	- Use of Landsat and Sentinel 2 (NDVI, vigor, chlorophyl and water stress, 10m resolution, 5 days frequency)	- On-farm weather station - Automatic traps	n/a	- Forecast models for yield development - Field mapping and modelling for variable rate fertilization
Agricon	n/a	- Yara N-sensor (vehicle-mounted)	n/a	n/a
Conservis / Climate FieldView	- Satellite Images	- Yara N-sensor (vehicle-mounted)	n/a	n/a
CropSat	- Satellite imagery from Landsat 8 (30m) and Sentinel 2 (10m) providing multispectral images for calculation of yield measures e.g. NDVI	n/a	n/a	n/a
FarmersEdge	- Satellite images	- Real-time soil moisture probes (root zone water content with multi-layer soil moisture and soil temperature measurement at 6 depths) - On farm weather stations	Applied but not described	- Growth stage models - Pest and insect models - Disease models - Ground-truthed models - Based on field data, agronomic data, machine learning and AI analytics
FarmNET	- Suggested but not described	- Suggested but not described	n/a	- Proposing to model health, soil health, biomass, climate, yield, footprint emissions water consumption, land demand - Evolution of farm as discrete–time stochastic dynamical system
LandCaRe	-Land cover data	n/a	n/a	- TREND, SEASON, FREQUENCY: Statistical models for long-term climate data analysis - LANUDIS: Stochastic model for scenario-dependent land use distribution

				- VEGPER, PHENO, ONTO, BAGLUVA, YIELDSTAT, GLPROD: Statistical models for ecological parameters (vegetation period, crop development, yield estimation, water balance) - SVAT-CN, MONICA: Process-based and dynamic process models for primary production and water use efficiency of non-agricultural vegetation, range of state variables describing crop and soil processes) - EROSION, IRRINEED, IRRIWATER: empirical, empirical/statistical models for erosion risk potential, crop irrigation - FECG, RAUMIS: Coefficient generator and agro-economy model for farm economy, maps for crop yield, irrigation worthiness and revenues
NaLamKi	- Multi-scale data acquisition with various satellites (Sentinel 1 and 2, Planet Labs with 4m resolution) - Remoting sensing of plant infections using UAV or satellites	- Soil sensors mentioned but not described - Data collection from sensors mounted on field robots (position, LiDAR, RGB and multispectral) to detect plant phenology e.g. fruit ripeness and plant condition	AI analysis and pattern recognition for improved perception of the environment and optimised operational planning	AI modelling
NEXT Farming	- Satellite Images - UAV	- NEXT GreenSeeker (vehicle mounted) - On farm weather station	n/a	Forecasting models
SMAG	- Satellite Images - UAV	- On farm weather station	n/a	n/a
Topcon Agriculture Platform (TAP)	n/a	- Yield Monitoring - Yara N-sensor (vehicle-mounted)	n/a	n/a
Trimble Farmer Pro/Advisor Prime	- Satellite Images with PurePixel™ calibrator	- In-Field Yield Monitoring	n/a	n/a

2.3 The DAKIS

2.3.1 Mapping ecosystem services and biodiversity potentials

For the estimation of yield potentials, we subdivide fields into patches of spatially connected subparts with different yield capacity. The delineation of patches is generated through automated analysis of multi-year yield maps and subsequent cluster analysis, adopting a knowledge-based approach that takes into account within-field heterogeneity to divide fields into subparts with homogeneous site-specific characteristics (Donat et al., 2022). These patches are machine-manageable, as maximum working widths are considered in the analysis, and they are oriented on the field in such a way that previously used permanent traffic lanes can still be used.

For the estimation of erosion control potential, we determine the optimal erosion control that can be achieved via agricultural land use and management in comparison to current levels (Melzer and Bellingrath-Kimura, 2021). First, erosion is calculated using high-resolution relief data from Airborne Laser Scanning (Farid et al., 2008), soil data from in-situ assessments (Panagos et al., 2014), rain data from 17 C-band Doppler radar systems (Auerswald et al., 2019) and observed crop rotations based on the European integrated administration and control system (Stein and Steinmann, 2018). A map of waterbodies is included to calculate sediment transport into aquatic ecosystems. The input data are processed using the open-source software InVEST SDR (The Natural Capital Project, version 3.9) (Sharp et al., 2020). To calculate erosion control potential, we estimate the difference in erosion under current crop rotations and a best-case land use scenario with permanent grassland, which causes the best degree of soil coverage and thus highest erosion control (Wang et al., 2016). The resulting raster data set is further processed by threshold analysis in ArcGIS Pro (Version 2.4.1) to identify small-scale erosion hotspots for which there is high improvement potential.

With respect to floristic biodiversity, we monitor the occurrence of indicator or character species, commonly used in Germany to determine high nature value (HNV) grasslands. To identify and localize the indicator plant species on grassland imagery, we train an object detection model based on a convolutional neural network (Basavegowda et al., 2022). The model uses images of selected species (*Armeria maritima, Campanula patula, Cirsium oleraceum, Daucus carota)* collected at 15-day intervals during their vegetative growth phase. This object detection model can be readily applied to grassland images to search for indicator species, and then species recognition can be linked to the HNV farmland (extensive grassland) type and its quality classes. The model will be evaluated on the UAV imagery to distinguish HNV grassland from non-HNV grassland and to differentiate the three HNV quality classes (Benzler et al., 2015).

2.3.2 Agroecological simulation modelling

The SIMPLACE modelling framework, used for the simulation of production and environmental dynamics, is based on the concept of combining interchangeable software units (SimComponents) that represent distinct biophysical processes in an agroecosystem. Presently, it contains more than 60 SimComponents for processes affecting biomass production, crop yield and nutrient content of a large range of crops, and selected ESS like ground water recharge, nitrate leaching, soil carbon sequestration, and GHG emissions in cropland and grassland systems (see www.simplace.net). In the frame of the DAKIS, we use the existing system components to model the ESS outlined above, and develop new approaches to simulate diversified cropping systems and to enrich the model by interfacing with other digital technologies. Specifically, we develop methods to represent intercropping systems with different spatial arrangements of trees and crops and apply new methods of assimilation of remotely sensed data into model runs (Tewes et al., 2020).

The microclimate model algorithm, setting off from the observation that air temperature inside forests is usually cooler than air temperature in open agricultural landscapes (Ghafarian et al., 2022a), calculates the amount of temperature reduction in the distance of woody landscape features, depending on their spatial extent and shape. Any change of the landscape composition by adding or removing trees and hedges in order to improve the total service provisioning of the land will result in changes of the cooling effect, which the DAKIS will quantify and provide for the decision process. The same applies for irrigation of crops, where the additionally evaporating and transpiring water contributes to landscape-scale cooling (Ghafarian et al., 2022b).

The approach on biodiversity modelling allows quantifying effects of management and landscape configuration scenarios on simple biodiversity indicators addressing single species, functional groups or overall species abundance and richness. It makes use of data that is continuously collected via acoustic sensors for bird, bat and *Orthoptera* species (single species or soundscape indices), and multi-scale remote sensing techniques for plant species diversity. These methods allow long-term monitoring of different species at near-real time and under different management scenarios and increasingly reliable and accurate predictions of the Bayesian networks, as new evidence is included over time.

2.3.3 Agro-economic optimisation modelling

The economic analysis of production options builds on the existing bio-economic modelling system MODAM (Zander and Kächele, 1999) that produces optimal land use, management, and investment plans. In DAKIS, we extend MODAM by including detailed price and yield risk assessments and risk preferences of farmers, which under conditions of climate change and quickly changing markets are becoming increasingly relevant, especially with respect to investment decisions (Ahmed et al., 2021; Guo et al., 2021; Talari et al., 2021). Within the DAKIS system, MODAM benefits from a coupling with SIMPLACE and the component on AI management pre-design, which provide detailed information on yields and ESS at sub-field or field level and specific management options including more ESS and biodiversity-oriented production systems.

2.3.4 Social-ecological agent-based modelling

The ViSA model is an extension to the VIABLE (*Values and Investments from Agent-Based interaction and Learning in Environmental systems*) model that has been developed and discussed in BenDor et al. (2009) Eisenack et al. (2006) and Scheffran and BenDor (2009) and later gathered in BenDor and Scheffran (2018). The basic principles of the ViSA model is to depict system evolution as a result of the interaction between several actors' groups with each other and with the ecological system that provides them with benefits from ESS in agricultural landscapes. Actors allocate part of their efforts that originates from different types of capitals (i.e., financial, social, natural, physical, cultural and human) to increase the supply of the ESS of interest. These ESS have a unit utility (i.e., price) which also spreads over these different types of capitals. In some locations in the landscape, several actors show demands for ESS that have tradeoff nature. This issue triggers conflicts between actors. Thus, they decide either to compete or to cooperate with actors sharing demands in the same location. Actors attempt to compromise between the viability of their capitals and the viability of the ecological system via satisfying their demands for ESS.

2.4 The DAKIS use case and GUI

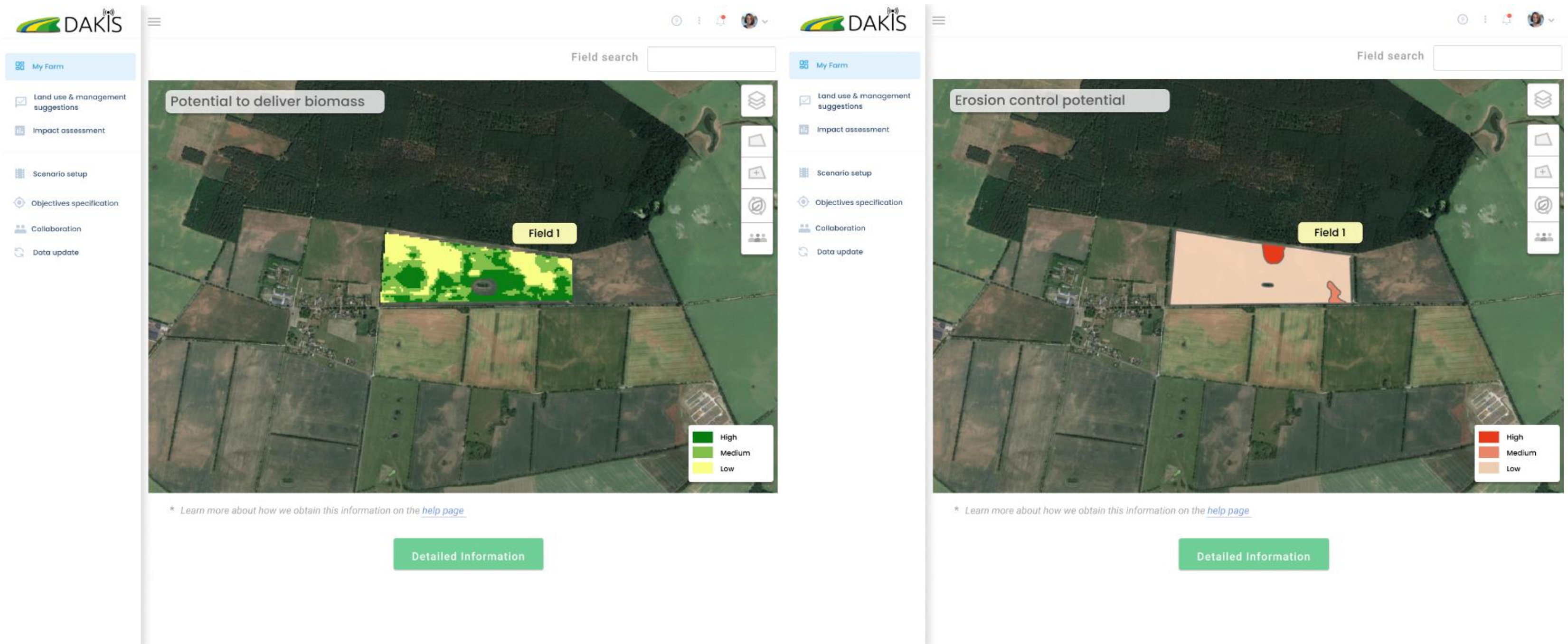

Figure S1. Sketches from the DAKIS GUI on the grassland buffer patches use case on the output 'Areas with high ESS and biodiversity potentials'.

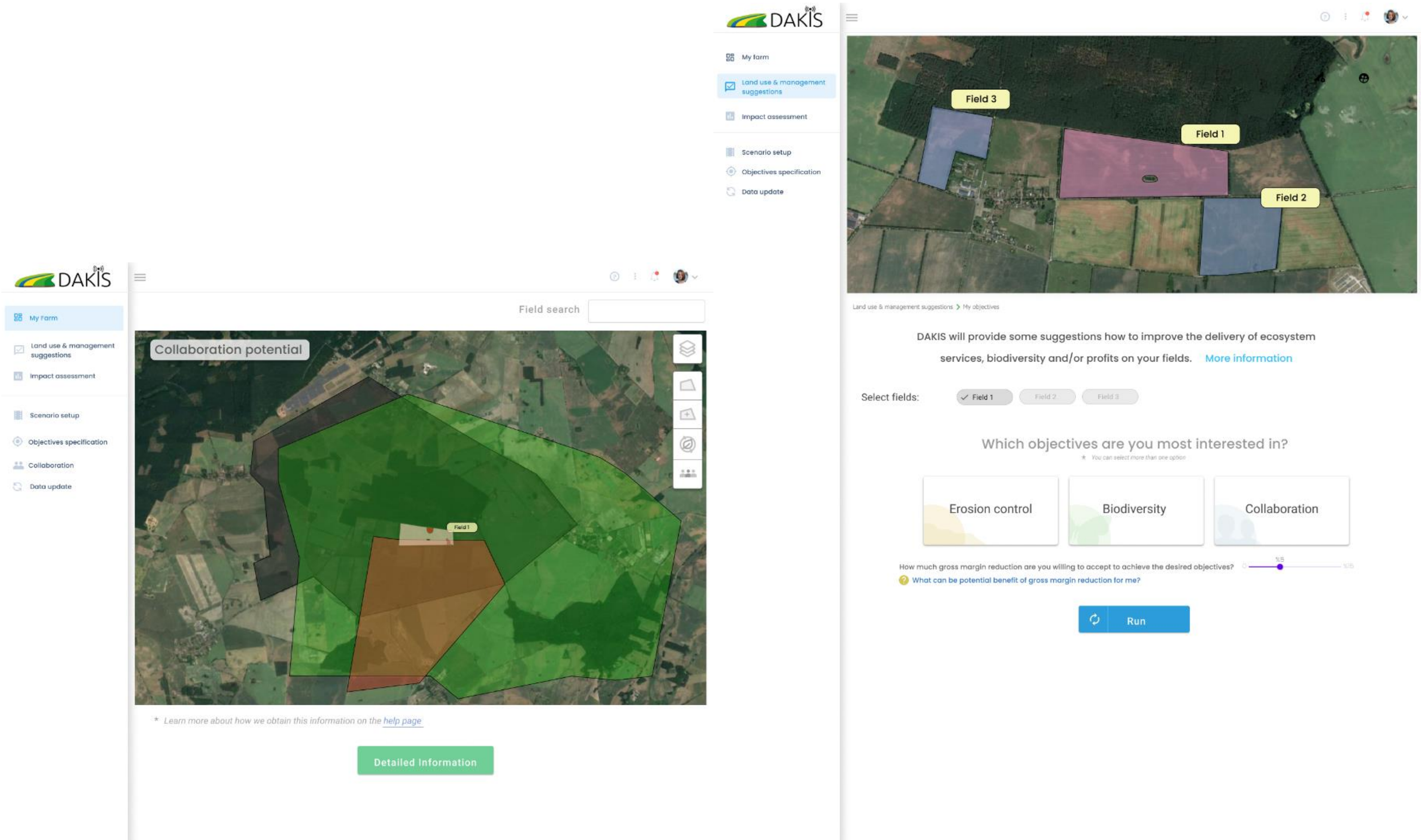

Figure S2. Sketches from the DAKIS GUI on the grassland buffer patches use case on the component 'Mapping demand for ESS and biodiversity potentials' and user input on 'Farmers' objectives on ESS and biodiversity'.

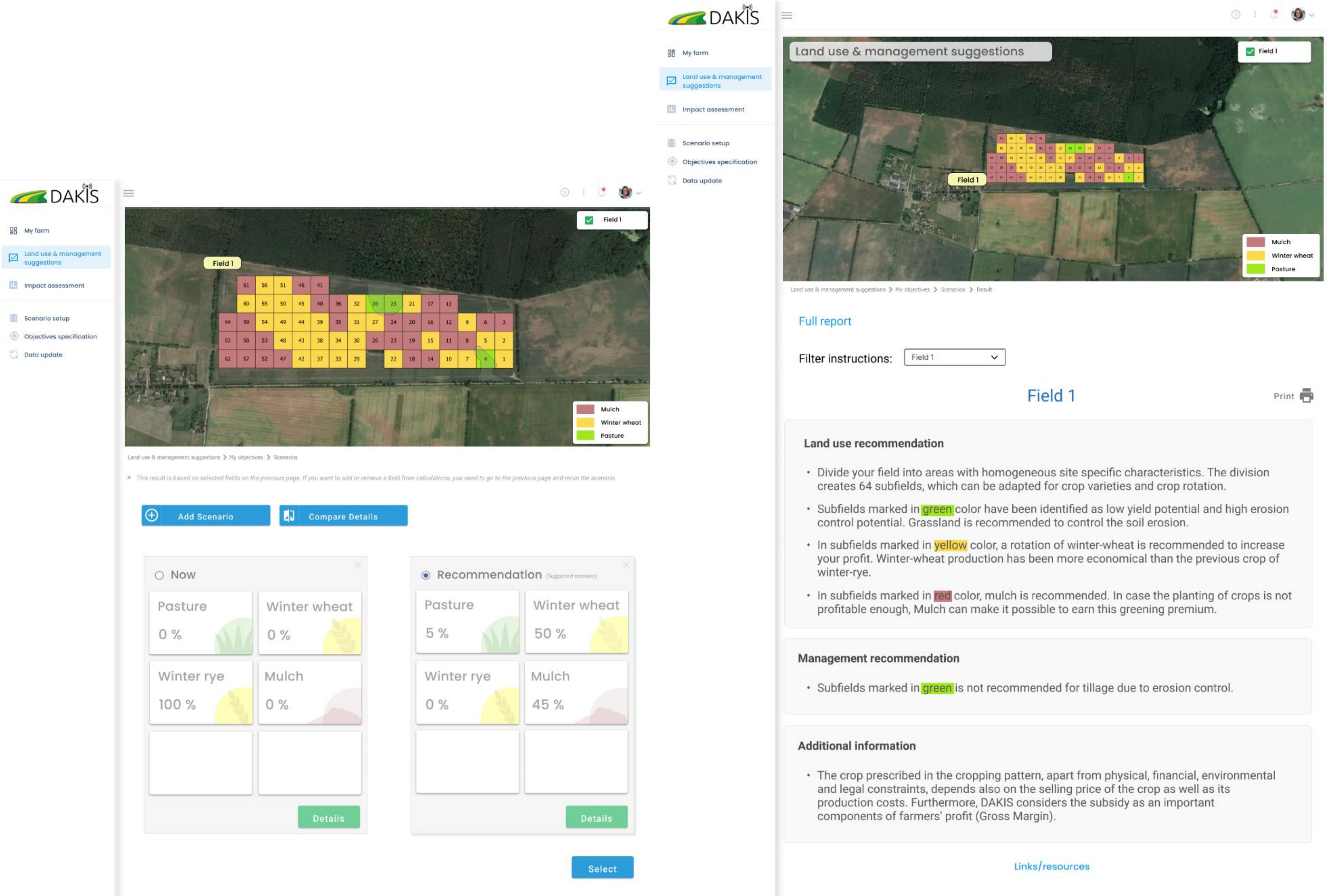

Figure S3. Sketches from the DAKIS GUI on the grassland buffer patches use case on the outputs 'Optimal land use and management patterns and income' and 'Land use and management suggestions and impacts'.

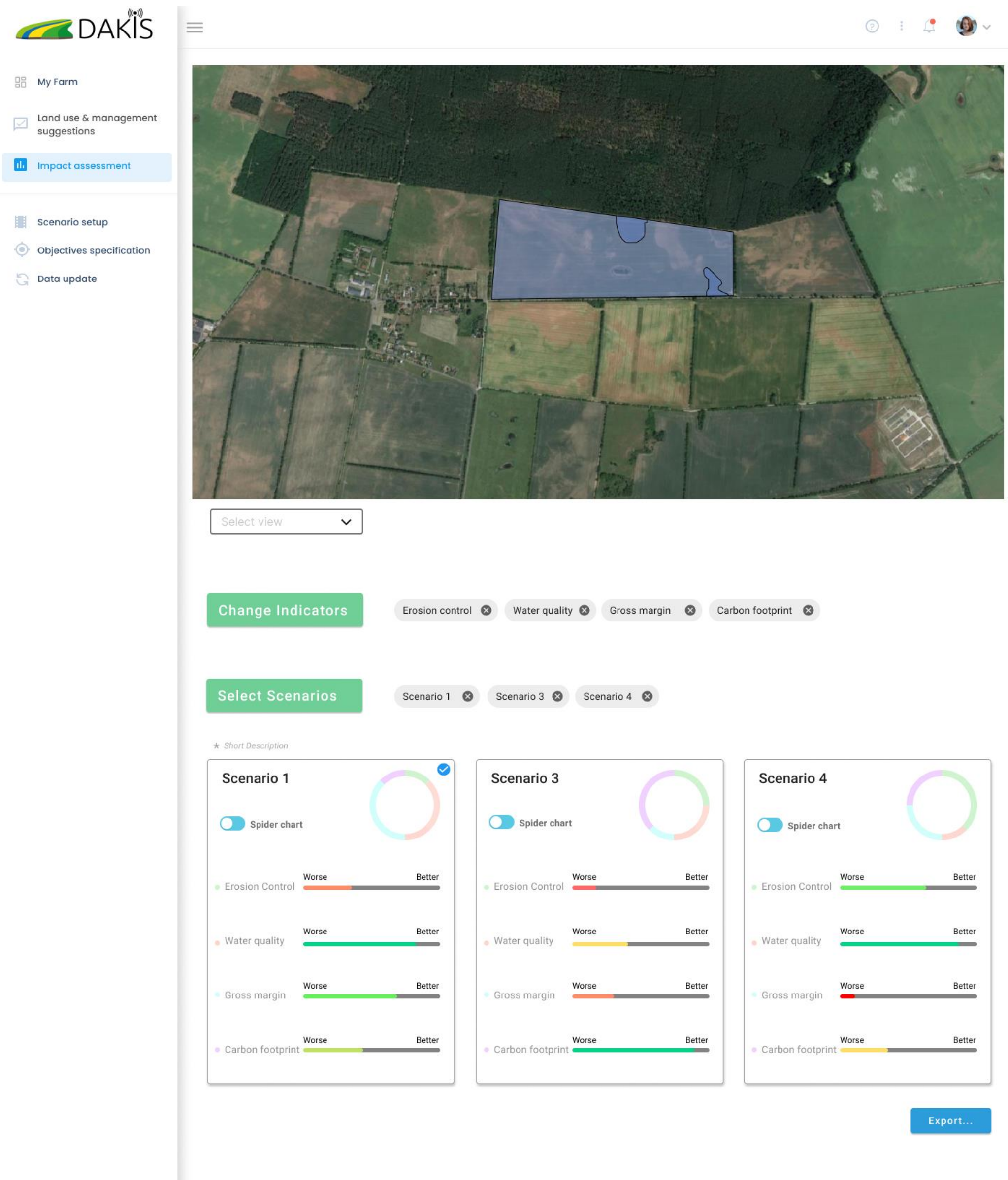

Figure S4. Sketches from the DAKIS GUI on the grassland buffer patches use case on the outputs 'Wider sustainability impacts'.

References

365FarmNet, 2021. 365FarmNet [WWW Document]. URL https://www.365farmnet.com/en/company/#_about (accessed 1.19.22).

AGRAVIS Digital GmbH, 2021. AGRAVIS NetFarming [WWW Document]. URL https://www.netfarming.de/de/netfarming_de/index.html (accessed 1.22.22).

Agricolus, 2021. Agricolus [WWW Document]. URL https://www.agricolus.com/en/ (accessed 1.19.22).

Agricon, 2022. Agricon [WWW Document]. URL https://www.agricon.de/ (accessed 2.3.22).

Agrinavia, 2022. Agrinavia. IT Management for plant production [WWW Document]. URL https://agrinavia.com/ (accessed 2.3.22).

Ahmed, Z., Guha, G.S., Shew, A.M., Alam, G.M.M., 2021. Climate change risk perceptions and agricultural adaptation strategies in vulnerable riverine char islands of Bangladesh. Land Use Policy 103, 105295. https://doi.org/10.1016/j.landusepol.2021.105295

Akkerweb, 2021. Akkerweb [WWW Document]. URL https://akkerweb.eu/de-de/ (accessed 2.3.22).

Arvato Systems GmbH, 2022. farmpilot [WWW Document]. URL https://www.arvato-systems.de/farmpilot (accessed 2.3.22).

Auerswald, K., Fischer, F.K., Winterrath, T., Brandhuber, R., 2019. Rain erosivity map for Germany derived from contiguous radar rain data. Hydrol. Earth Syst. Sci. 23, 1819–1832. https://doi.org/10.5194/hess-23-1819-2019

Basavegowda, D.H., Mosebach, P., Schleip, I., Weltzien, C., 2022. Indicator plant species detection in grassland using EfficientDet object detector., in: 42. GIL-Jahrestagung - Was Bedeutet Künstliche Intelligenz Für Die Agrar- Und Ernährungswirtschaft? Gesellschaft für Informatik e.V., Bonn, pp. 57–62.

BASF Digital Farming GmbH, 2022. xarvio Digital Farming Solutions [WWW Document]. URL https://www.xarvio.com/de/de.html (accessed 2.3.22).

BenDor, T., Scheffran, J., 2018. Agent-Based Modeling of Environmental Conflict and Cooperation. CRC Press (Verlag).

BenDor, T., Scheffran, J., Hannon, B., 2009. Ecological and economic sustainability in fishery management: A multi-agent model for understanding competition and cooperation. Particip. Eval. Sustain. River Basin Gov. 68, 1061–1073. https://doi.org/10.1016/j.ecolecon.2008.07.014

Benzler, A., Fuchs, D., Hüning, C., 2015. Methodik und erste Ergebnisse des Monitorings der Landwirtschaftsfläche mit hohem Naturwert in Deutschland. Beleg für aktuelle Biodiversitätsverluste in der Agrarlandschaft. Nat. Landsch. 90, 309–316.

Claas, 2022. AGROCOM NET. Die Umfassende Schlagkartei Für Den Effizienten Pflanzenbau [WWW Document]. URL https://www.claas.de/produkte/easy/farm-management-software/pflanzenbau (accessed 2.3.22).

Climate FieldView, 2020. Climate FieldView [WWW Document]. URL https://climatefieldview.de/ (accessed 1.20.22).

Conservis, 2021. Conservis [WWW Document]. URL https://conservis.ag/ (accessed 1.19.22).

Crop SRM, Farmflo, Farm Flo Limited, 2021. Crop SRM [WWW Document]. URL https://cropsrm.com/ (accessed 2.3.22).

da Fonseca, E.P.R., Caldeira, E., Ramos Filho, H.S., e Oliveira, L.B., Pereira, A.C.M., Vilela, P.S., 2020. Agro 4.0: A data science-based information system for sustainable agroecosystem management. Simul. Model. Pract. Theory 102. https://doi.org/10.1016/j.simpat.2020.102068

Debeljak, M., Trajanov, A., Kuzmanovski, V., Schröder, J., Sandén, T., Spiegel, H., Wall, D.P., Van de Broek, M., Rutgers, M., Bampa, F., Creamer, R.E., Henriksen, C.B., 2019. A field-scale decision support system for assessment and management of soil functions. Front. Environ. Sci. https://doi.org/10.3389/fenvs.2019.00115

DELOS, 2022. DELOS [WWW Document]. URL https://www.delos.biz (accessed 2.3.22).
Donat, M., Geistert, J., Grahmann, K., Bloch, R., Bellingrath-Kimura, S.D., 2022. Patch cropping- a new methodological approach to determine new field arrangements that increase the multifunctionality of agricultural landscapes. Comput. Electron. Agric. 197, 106894. https://doi.org/10.1016/j.compag.2022.106894
eFeldkalender GmbH, 2022. eFeldkalender [WWW Document]. URL https://feldkalender.ch (accessed 2.3.22).
Eisenack, K., Scheffran, J., Kropp, J.P., 2006. Viability analysis of management frameworks for fisheries. Environ. Model. Assess. 11, 69–79. https://doi.org/10.1007/s10666-005-9018-2
Farid, A., Goodrich, D.C., Bryant, R., Sorooshian, S., 2008. Using airborne lidar to predict Leaf Area Index in cottonwood trees and refine riparian water-use estimates. J. Arid Environ. 72, 1–15. https://doi.org/10.1016/j.jaridenv.2007.04.010
Farmdok GmbH, 2021. Farmdok [WWW Document]. URL https://www.farmdok.com/en/ (accessed 2.3.22).
FarmersEdge, 2022. FarmersEdge [WWW Document]. URL https://www.farmersedge.ca/ (accessed 1.20.22).
FARMserver, 2020. FARMserver [WWW Document]. URL https://www.farmserver.com/ (accessed 2.3.22).
FieldTRAKS Solutions Inc, 2019. FieldTRAKS [WWW Document]. URL https://www.fieldtraks.ca/ (accessed 2.3.22).
Ghafarian, F., Wieland, D., Lüttschwager, D., Nendel, C., 2022a. Application of XGBoost and SHAP to predict inside-forest temperature regimes from standard open-field meteorological data. Environmetal Model. Softw. Under revision.
Ghafarian, F., Wieland, R., Nendel, C., 2022b. Estimating the evaporative cooling effect of irrigation within and above the crop canopy. MDPI Water Under review.
Guo, H., Wang, R., Garfin, G.M., Zhang, A., Lin, D., Liang, Q., Wang, J., 2021. Rice drought risk assessment under climate change: Based on physical vulnerability a quantitative assessment method. Sci. Total Environ. 751, 141481. https://doi.org/10.1016/j.scitotenv.2020.141481
Hauer, L., Wischenbart, M., Handl, L., Datzberger, M., Prankl, P., Handler, F., Polly, S., 2019. Geo-Informations-Systeme für teilflächenspezifische Bewirtschaftungsmethoden zur Effizienzsteigerung und Ökologisierung in der österreichischen Landwirtschaft (GIS-ELA), in: 39. GIL-Jahrestagung, Digitalisierung Für Landwirtschaftliche Betriebe in Kleinstrukturierten Regionen-Ein Widerspruch in Sich?.
HELM-Software, 2022. Myfarm24 [WWW Document]. URL https://helm-software.de/ (accessed 2.3.22).
Honda, K., Ines, A.V., Yui, A., Witayangkurn, A., Chinnachodteeranun, R., Teeravech, K., 2014. Agriculture information service built on geospatial data infrastructure and crop modeling. Proc. 2014 Int. Workshop Web Intell. Smart Sens. 1–9.
ISAGRI GRUPPE. COBERA-Land GmbH, 2022. Ackerbau, eLMID [WWW Document]. URL https://www.elmid.de/ackerbau/ (accessed 2.3.22).
Kenny, U., Regan, A., 2021. Co-designing a smartphone app for and with farmers: Empathising with end-users' values and needs. J. Rural Stud. 82, 148–160. http://dx.doi.org/10.1016/j.jrurstud.2020.12.009
Lindblom, J., Lundström, C., Ljung, M., Jonsson, A., 2017. Promoting sustainable intensification in precision agriculture: review of decision support systems development and strategies. Precis. Agric. 18, 309–331.
López-Riquelme, J.A., Pavón-Pulido, N., Navarro-Hellín, H., Soto-Valle, F., Torres-Sánchez, R., 2017. A software architecture based on FIWARE cloud for Precision Agriculture. Agric. Water Manag. 183.
LV digital GmbH, 2021. top farmplan [WWW Document]. URL https://www.topfarmplan.de (accessed 2.3.22).

Maschinenringe Deutschland GmbH, 2022. MeinAcker [WWW Document]. URL https://apps.maschinenring.de/meinacker/ (accessed 2.3.22).
Melzer, M., Bellingrath-Kimura, S., 2021. GIS-gestützte Modellierung von Ökosystemleistungen - Status quo, Potenziale und Trade-offs, in: Meyer-Aurich, A., Gandorfer, M., Hoffmann, C., Weltzien, C., Bellingrath-Kimura, S., Floto, H. (Eds.), 41. GIL-Jahrestagung, Informations- Und Kommunikationstechnologie in Kritischen Zeiten. Gesellschaft für Informatik e.V., Bonn, pp. 199–204.
NaLamKi, 2021. Nachhaltige Landwirtschaft mit Künstlicher Intelligenz [WWW Document]. URL https://nalamki.de/ (accessed 1.20.22).
NEXT Farming, 2022. Für eine Landwirtschaft der Zukunft - NEXT Farming [WWW Document]. URL https://www.nextfarming.de/landwirt/ (accessed 1.20.22).
Panagos, P., Meusburger, K., Ballabio, C., Borrelli, P., Alewell, C., 2014. Soil erodibility in Europe: A high-resolution dataset based on LUCAS. Sci. Total Environ. 479–480, 189–200. https://doi.org/10.1016/j.scitotenv.2014.02.010
PEAT GmbH c/o Plantix, 2022. Plantix [WWW Document]. URL https://plantix.net/en/ (accessed 2.3.22).
Plantivo GmbH, 2022. Plantivo Agrarsoftware [WWW Document]. URL https://www.plantivo.de/ (accessed 2.3.22).
Scheffran, J., BenDor, T., 2009. Bioenergy and land use: a spatial-agent dynamic model of energy crop production in Illinois. Int. J. Environ. Pollut. 39, 4–27.
Sharp, R., Tallis, H.T., Ricketts, T., Guerry, A.D., Wood, S.A., Chaplin-Kramer, R., Nelson, E., Ennaanay, D., Wolny, S., Olwero, N., Vigerstol, K., Pennington, D., Mendoza, G., Aukema, J., Foster, J., Forrest, J., Cameron, D., Arkema, K., Lonsdorf, E., Kennedy, C., Verutes, G., Kim, C.K., Guannel, G., Papenfus, M., Toft, J., Marsik, M., Bernhardt, J., Griffin, R., Glowinski, K., Chaumont, N., Perelman, A., Lacayo, M., Mandle, L., Hamel, P., Vogl, A.L., Rogers, L., Bierbower, W., Denu, D., Douglass, J., 2020. InVEST 3.8.4.post3+ug.g3731663 User's Guide. The Natural Capital Project, Stanford University, University of Minnesota, The Nature Conservancy, and World Wildlife Fund. [WWW Document]. URL https://storage.googleapis.com/releases.naturalcapitalproject.org/invest-userguide/latest/index.html (accessed 6.18.20).
SMAG, 2021. SMAG : Welcome to the Smart Agriculture - Agricultural Softwares [WWW Document]. URL https://en.smag.tech/ (accessed 1.20.22).
SmartCloudFarming [WWW Document], 2021. URL https://smartcloudfarming.com (accessed 2.3.22).
Soonapse, 2018. Ploovium [WWW Document]. URL https://www.ploovium.com (accessed 2.3.22).
Stadtmann, W., 2022. Ackermanager, Agrarsoftware Stadtmann [WWW Document]. URL https://agrarsoft-stadtmann.de/html/ackermanager.html (accessed 2.3.22).
Stein, S., Steinmann, H.-H., 2018. Identifying crop rotation practice by the typification of crop sequence patterns for arable farming systems – A case study from Central Europe. Eur. J. Agron. 92, 30–40. https://doi.org/10.1016/j.eja.2017.09.010
Talari, G., Cummins, E., McNamara, C., O'Brien, J., 2021. State of the art review of Big Data and web-based Decision Support Systems (DSS) for food safety risk assessment with respect to climate change. Trends Food Sci. Technol. https://doi.org/10.1016/j.tifs.2021.08.032
Tewes, A., Hoffmann, H., Krauss, G., Schäfer, F., Kerkhoff, C., Gaiser, T., 2020. New Approaches for the Assimilation of LAI Measurements into a Crop Model Ensemble to Improve Wheat Biomass Estimations. Agronomy 10. https://doi.org/10.3390/agronomy10030446
The Yield AgTech Solutions, 2021. Sensing+ [WWW Document]. URL https://www.theyield.com/ (accessed 2.3.22).
Topcon Corporation, Topcon Positioning Group, 2019. Topcon Agriculture Platform [WWW Document]. URL https://tap.topconagriculture.com/farmer/ (accessed 2.3.22).

Trimble Agriculture, Trimble Inc., 2022. Farmer Pro [WWW Document]. URL https://agriculture.trimble.de/product/farmer-pro-verwenden/ (accessed 2.3.22).
Wang, R., Zhang, S., Yang, J., Pu, L., Yang, C., Yu, L., Chang, L., Bu, K., 2016. Integrated Use of GCM, RS, and GIS for the Assessment of Hillslope and Gully Erosion in the Mushi River Sub-Catchment, Northeast China. Sustainability 8, 317. https://doi.org/10.3390/su8040317
Wenkel, K.O., Berg, M., Mirschel, W., Wieland, R., Nendel, C., Kröstner, B., 2013. LandCaRe DSS–An interactive decision support system for climate change impact assessment and the analysis of potential agricultural land use adaptation strategies. J. Environ. Manage. 168–183.
Zander, P., Kächele, H., 1999. Modelling multiple objectives of land use for sustainable development. Agric. Syst. 59, 311–325. https://doi.org/10.1016/S0308-521X(99)00017-7
Zheleva, M., Bogdanov, P., Zois, D.S., Xiong, W., Chandra, R., Kimball, M., 2017. Smallholder agriculture in the information age: Limits and opportunities, Proceedings of the 2017 Workshop on Computing Within Limits.