Agricultural Systems 217 (2024) 103950

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Co-designing a landscape experiment to investigate diversified cropping systems

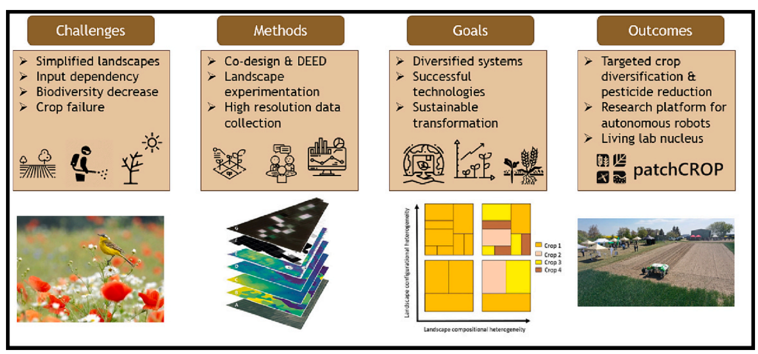
Kathrin Grahmann [a,*], Moritz Reckling [a,b], Ixchel Hernández-Ochoa [c], Marco Donat [a,d], Sonoko Bellingrath-Kimura [a,d], Frank Ewert [a,c]

[a] Leibniz Centre for Agricultural Landscape Research (ZALF), 15374 Müncheberg, Germany
[b] Department of Crop Production Ecology, Swedish University of Agricultural Sciences (SLU), 750 07 Uppsala, Sweden
[c] University of Bonn, Institute of Crop Science and Resource Conservation (INRES), 53115 Bonn, Germany
[d] Department of Agronomy and Crop Science, Humboldt-University of Berlin, 14195 Berlin, Germany

HIGHLIGHTS

- Impacts of crop diversification are studied in a landscape experiment.
- Farmer's perspective was successfully included in the design of a complex experiment.
- Landscape experiments generate systemic agroecosystem knowledge.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Kairsty Topp

Keywords:
Biodiversity
Ecosystem services
DEED
Digitalization
On-farm experimentation
Soil heterogeneity

ABSTRACT

CONTEXT: Intensive food and feed production in sole-cropped, large fields with high fertilizer and pesticide inputs to achieve high yields, has contributed to detrimental environmental impacts. To move towards more sustainable agricultural landscapes, cropping system diversification has been suggested as a promising practice for which the use of digital technologies could be potentially beneficial. Understanding the impact of diversified, newly arranged cropping systems and their management requires long-term experimental data at the landscape scale and practical experiences in using digital technologies which are hardly available. Experimental platforms in an agricultural landscape setup with farmers' involvement could meet such demands but have not been set up in many regions nor has the process of designing such platforms been described systematically.
OBJECTIVE: The overall objective of this study was to describe how an experimental platform can be co-designed jointly by researchers and practitioners to study and understand the impact of diversification practices compared to current cropping systems in Eastern Brandenburg, Germany. Specifically, we aimed to re-design an intensively managed field into smaller field segments that we called patches and to assess the potential of a co-created landscape experiment for sustainable agricultural production focussing on both, the practitioners ́ and scientists ́ perspective.

* Corresponding author.
E-mail address: Kathrin.Grahmann@zalf.de (K. Grahmann).

https://doi.org/10.1016/j.agsy.2024.103950
Received 3 January 2024; Received in revised form 20 March 2024; Accepted 5 April 2024
Available online 13 April 2024

METHODS: We used the DEED research cycle (Describe, Explain, Explore and Design) as a conceptual framework to co-design the landscape experiment called patchCROP within a commercial farm. Patches were implemented as 0.5 ha fields within the original field based on yield and soil maps using advanced cluster analysis which considered soil heterogeneity. The original narrow crop sequence was diversified by integrating new crops, cover crops and flower strips for a five-year crop rotation. To cultivate the patches, large machinery was used during the first years but will be replaced over time with autonomous field robots. Workshops and various methods such as a SWOT analysis were used to adjust the management practices towards pesticide reduction.
RESULTS AND CONCLUSIONS: The SWOT analysis revealed opportunities and drawbacks to develop such a research platform in a participative manner from both the scientific and practical farming perspective. We found that the farmer-centric position focused mainly on the economic return and feasibility of future field operations in the diversified field. The scientific perspective on the other hand described needs and potentials about the research process for evaluating dynamic, interdependent or opposing natural processes and their interactions like productivity, biodiversity and ecosystem service changes in an agricultural landscape context.
SIGNIFICANCE: Co-designed landscape experiments have the potential to simultaneously assess the impact of newly developed cropping systems on biodiversity and ecosystem services beyond the field level, crop performance and soil quality at multiple scales, and the implications for multiple actors. This is a step forward to extend systems-based research from single plot to landscape research in an on-farm environment, allowing the exploration of diversification measures with new digital technologies in the long run.

1. Introduction

Agricultural intensification, characterized by large-scale farming, increased chemical pesticide and mineral fertilizer use, and intensive tillage, has been widely associated with declines in biodiversity and rising production uncertainties (Batáry et al., 2017; Benton et al., 2003; Hufnagel et al., 2020). Climate change further exacerbates yield losses and production risks under intensive systems with limited crop and management diversity (Webber et al., 2020). To address these challenges and move towards agroecological intensification, defined as the incorporation of ecological principles and biodiversity management into agricultural system to increase yields and decrease external inputs, crop diversification has emerged as a crucial strategy (Ewert et al., 2023; Garbach et al., 2017; Sirami et al., 2019; Wezel et al., 2014). Crop diversification measures can be classified into spatial and temporal strategies. Spatial diversification involves measures for improved habitat connectivity, smaller field sizes, intercropping and higher field edge density, while temporal diversification includes varying and extended crop rotations (Davis et al., 2012; Fahrig et al., 2011; Juventia et al., 2022). Genetic diversification through cultivar and species mixtures is a third dimension for diversified cropping (Ditzler et al., 2021). Crop diversification promotes biodiversity and enhances ecosystem services like nutrient cycling and water regulation without compromising productivity (Tamburini et al., 2020; Tscharntke et al., 2021). Although many diversification measures are physically implemented at and within the field scale, environmental and ecological processes take place at the landscape level and are interrelated (Reckling et al., 2023). The landscape scale in this study is delineated by its agricultural context, being a mosaic (composition and configuration) of land use and land cover spread over 830 ha (Pereponova et al., 2023b).

Among spatial diversification practices, field size reduction has been extensively studied for its positive effects on biodiversity and natural pest regulation (Bosem Baillod et al., 2017; Sirami et al., 2019). Hass et al. (2018) found that smaller field size promoted pollinator populations, but authors did not determine field-size effects on crop yields. Field boundary density (equivalent to edge density defined as the sum of all field boundaries per total area under cropping) plays a particularly important role for bumblebees (Marshall et al., 2006). The aphid incidence in wheat fields was significantly reduced by small field sizes and a high density of grassy field boundaries (Bosem Baillod et al., 2017). It has been pointed out that smaller fields lead to higher labour input and costs and are more difficult to get planned for production processes (Clough et al., 2020). The implementation of manipulative experiments to investigate new field arrangements is complex and challenging, as all factors need to be measurable at the same time. Crop physiological, ecological (including soil, water and species dynamics) and technological parameters of field size reduction have to be collected to capture biodiversity and agronomic processes and performance.

Landscape experiments are defined as a specialized research approach explicitly designed to investigate and gather empirical data on multiple processes and mechanisms that occur within an agricultural landscape and distinguish in size, duration and experimental design from common field or plot experiments in agricultural science (Pereponova et al., 2023a). To our knowledge, no systematic collection of biodiversity, ecosystem services and productivity data provided from soil and plant interactions by fragmentation of large fields into small-structured field units has been done yet. As shown by Kirchweger et al. (2020), more comprehensive evaluations are required to document effects of land use changes by decreasing field size and increasing field edges on biodiversity, ecosystem services and farm economics. Additionally, the monitoring of "slow processes" to evaluate long-term performance of diversified farming systems was graded as innovative and necessary research path (Prost et al., 2023). It is currently unknown how these envisaged changes of smaller field size will affect the long-term agroecosystem performance in terms of (a) competition and neighbour effects and (b) actual effects on adaptation to climate change, resource use efficiencies or pest and weed dynamics (Segoli and Rosenheim, 2012; Tscharntke et al., 2022).

In Eastern Germany, where agricultural fields exhibit considerable soil heterogeneity in terms of soil organic matter, soil texture and water holding capacity and have large sizes, efforts have been made to develop site-specific cropping strategies using precision agriculture and soil-based management zones (Bönecke et al., 2020; Premke et al., 2016). Here, we propose taking precision agriculture one step further by introducing "patch cropping", a novel field arrangement approach that considers field heterogeneity and landscape context combined with site-specific crop selection to increase multifunctionality of agricultural landscapes (Donat et al., 2022).

Digital tools are assumed to offer the potential for implementing agricultural diversification like patch cropping. New technological developments can accelerate the understanding, design, and management of diverse cropping systems (Chlingaryan et al., 2018). They can also increase efficiency (e.g. precision farming and technologies like variable rate application or controlled traffic farming) or substitute costly and potentially harmful inputs (e.g. alternative pest control systems such as mechanical weed control through camara-controlled systems) (Finger, 2023). However, the adoption of technologies like autonomous robots is still low and legal regulations pose challenges for their application (Basu et al., 2020; Oliveira et al., 2021). Consequently, there is a need for unbiased assessments to determine the benefits and drawbacks of these technologies in real-life settings among stakeholders (Tamirat et al., 2023). The establishment of landscape experiments that encompass both ecological and agronomic aspects of diversification is essential for innovative research supporting farmer-centric approaches (Estrada-Carmona et al., 2022; Reckling et al., 2020). Participatory research, involving farmers and scientists in all stages, is crucial for co-designing relevant research questions and finding farm-specific solutions for complex social, political, environmental and technological problems (Busse et al., 2023; Descheemaeker et al., 2019; Lacoste et al., 2021).

In this study, we aim to guide and facilitate the design and implementation of a landscape experimental platform focusing on cropping systems diversification supported by digital technologies. We seek to address experimental solutions for investigating more sustainable and resilient agricultural systems and identify opportunities and constraints of this experimental approach under on-farm conditions. The following research questions will be addressed:

(i) Which research process is needed with stakeholders for co-designing sustainable cropping systems that integrate crop diversification facilitated through digital technologies?
(ii) How can we develop and implement a landscape experiment that effectively promotes cropping systems diversification and incorporates digital technologies to address the challenges of sustainable agricultural intensification in Eastern Germany?
(iii) What are the opportunities and constraints associated with implementing crop diversification approaches under on-farm conditions in experimental landscape set-ups?

To answer the research questions, we adapted the DEED research cycle (Describe, Explain, Explore, and Design) as a conceptual framework (Giller et al., 2011; Reckling et al., 2020) to describe the set-up procedure of a landscape experiment in three phases and to explore novel management solutions for landscape diversification.

2. Materials and methods

2.1. Conceptual framework

We used the DEED research cycle to structure the co-design of the experiment, the implementation and adaptation of practices in an active exchange with various stakeholders. The DEED research cycle is one conceptual framework for the co-design of farming systems by operationalizing systems agronomy. The framework is adapted from Kolb's learning cycle (Kolb, 1984) and involves participatory work with farmers, modelling and experimentation in an iterative process. The DEED cycle supports the understanding of the complexity of farming and the generation of tailored options to re-design systems (Giller et al., 2011). The cycle consists of four generic steps that are also possible to be combined and extended: (i) Describe farming systems and their constraints, (ii) Explain the consequences of farming systems, (iii) Explore options for agro-technological improvement and innovation, and (iv) Design improved management systems. The cycle is used for co-learning by farmers, advisors and scientists, to identify which options fit best or explore innovations, and thus provides farm or landscape-specific solutions by using a combination of methods (Descheemaeker et al., 2019; Dogliotti et al., 2014; Falconnier et al., 2017). The involvement of the actors in all steps of the cycle supports the local relevance of the designed options (Reckling et al., 2020).

We adapted the framework to support the process interaction with a farmer network, individual farmers, and scientists during three main phases, i) concept phase for co-designing the landscape experiment, ii) consolidation phase for co-designing and adapting the management, and iii) implementation phase to co-design agricultural landscapes beyond the experiment, using several iterations of the DEED cycle (Fig. 1).

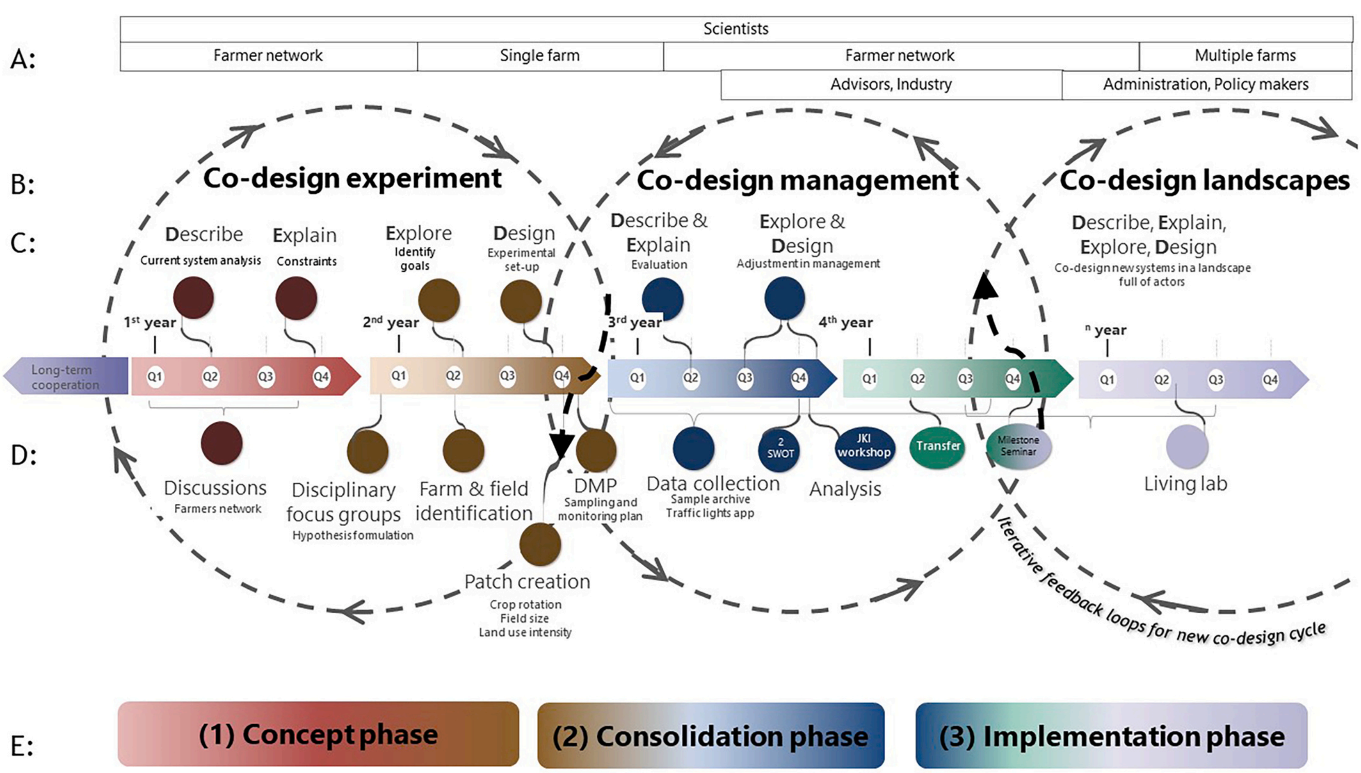


Fig. 1. Descriptive framework of different phases and steps applied in patchCROP to develop a landscape experiment using participatory approaches: (A) Levels of interaction and exchange: groups of involved actors and participating institutions, (B) DEED iteration cycles of past co-design of the landscape experiment, current co-design and adjustments of the management practices to successfully establish diversification in the landscape experiment and future co-design of agricultural landscapes at larger scales, (C) DEED cycle steps and exemplary outcomes that have been or will be reached in the applied innovation cycles, (D) Relevant actions and formats needed for the research success (DMP: data management plan), (E) Conceptual framework of three main phases to structure stakeholder interactions.

2.2. Co-design process

In the first phase, we co-designed the landscape experiment (Fig. 1 "Concept phase"). We described regional crop production and explained constraints and opportunities of farms in Brandenburg based on active exchange and regular activities with 14 farmers of a farmer network and an interdisciplinary group of scientists during 2019. Meetings were planned through agenda items, the discussion was documented, and protocols were shared, open for comments and additions to guarantee inclusion of all participants. Additionally, we reviewed the agro-economic and environmental impacts using available literature on German agricultural policies and environmental impact assessment.

The regional farmer network is located in two districts (Märkisch Oderland, Landkreis Oder-Spree) in the east of the federal state of Brandenburg (Germany) and comprises around 10 large conventional farms with an outstanding size of 1000 to 4000 ha per farm. The farms are mainly mixed farms (fattening cows and dairy cows, arable crops and bio-gas). The network exists for >20 years and is facilitated by agronomists from the Leibniz Centre for Agriculture Landscape Research (ZALF). The activities of the network include monthly on-farm meetings (always at another farm) to discuss pressing issues such as pest control, crop rotation planning, nutrient and carbon management, cover crops and caries out field visits at every meeting.

In a next step, research hypotheses were explored during internal focus groups at ZALF with around 20–30 scientists from several disciplines (agronomy, crop protection, soil science, crop modelling, proximal and remote sensing, socio-economy, field trial design, statisticians). For those bi-monthly meetings during 2019, the aim was to collect and formulate research objectives and hypotheses for a new landscape experimental platform considering the current challenges of crop production, knowledge gaps, as well as societal and political demands. Later on, the discussion was widened with 14 farmers from the regional farmer network to support the evaluation of social impacts on smart technologies and new field design (Rose et al., 2021) during 2019–2020. During the discussions with farmers, one farm was approached in January 2020 to establish the landscape experiment, and to realize different management strategies. For the experimental set-up, we re-designed one of the farms' most heterogeneous fields into smaller field units ("patches", thus "patchCROP" as name for this particular landscape experiment). For this purpose, proficient knowledge from frequent discussions and workshops with the identified farm and their managers (one business manager and one crop production manager, hereafter called farm managers) as well as scientists from different disciplines, i.e. agronomy, crop protection, biodiversity, soil sciences and remote and proximal sensing was merged. The first patches were planted in March 2020.

In the second phase (Fig. 1 "Consolidation phase"), we followed another DEED cycle, to co-design management practices with the identified farm. We first described and explained (evaluated) the experiences and preliminary results from the landscape experiment in a SWOT analysis, a framework and planning technique to assess Strengths, Weaknesses, Opportunities, and Threats (Weihrich, 1982). Then, we conduct regular workshops (2 times per year: after harvest of winter crops in July/August and after harvest of spring crops in November/December) and project meetings (monthly) for the adjustment of the selected diversification and pesticide reduction measures and their assessment strategies in the landscape experiment. To collect the opportunities and constraints of the landscape experimentation approach, two strategic SWOT analyses were conducted in the second year of the experiment in 2021, targeting to learn from the experiences made with patchCROP and how the experimental platform could potentially further develop to support agricultural landscape diversification. The first SWOT was realized in a workshop format with scientists of a wider disciplinary background from social and natural sciences and the second SWOT was generated during an interview with the farm managers of the identified farm. The first workshop was organized 14 months after the patchCROP implementation to work with >20 scientists using a digital white board (use of Mural software, a licenced digital workspace for visual collaboration) due to COVID-19 pandemic. Some of the participating scientists were involved in patchCROP related research activities, but most participants had an outside view on the project. Participants were asked to answer the question "How does patchCROP contribute to advance science on process understanding, co-design and digitalization in diversified agricultural landscapes?". The second exchange was conducted 15 months after the patchCROP initiation conducting a structured, but open face-to-face interview with the farm managers. They were asked to answer the question "How can a complex experimental platform like patchCROP be implemented under on-farm conditions to support diversified farm management and to increase the co-learning success between farmers and scientists?". The outcomes of both SWOT analysis were used to describe lessons learned, applicable across scales and disciplines, to capitalize on strengths and opportunities for the subsequent exploration and design steps to adjust and fine-tune diversification approaches and management decisions on pesticide reduction with the aim of advancing systems-based agricultural research.

The third phase has only been started by evaluating the first outcomes of the experimentation and co-design process and will continue in the future. It is intended to develop into a continuous cycle of co-design of new field arrangements at the landscape scale among key regional actors and multiple farms (Fig. 1 "Co-design landscapes") including innovations and technologies partly resulting from patchCROP activities of previous cycles.

2.3. Experimental site

The landscape experiment patchCROP was implemented in the eastern part of Brandenburg, Germany (52°27′07.5"N; 14°09′42.7″E). The region has an annual average temperature of 9.6 °C and an annual mean precipitation of 472 mm (Schirrmann et al., 2016). Its soil formation is characterized by the Weichselian young moraine landscape having differentiated deposition of glacial sediments and diverse post-glacial soil formation processes leading to high spatial variability of soil properties (Premke et al., 2016). According to the world reference soil base, the experimental site has three main soil types: Eutric Retisols, Geoabruptic Luvisols and Eutric Lamellic Brunic Arenosols.

3. Co-design of the landscape experiment

3.1. Describe and explain current cropping systems

Agricultural production in Brandenburg is dominated by winter crops with 21% winter rye, 16% winter oilseed rape, 13% winter wheat, 8% winter barley, and during the summer, silage maize for energy (19%) or fodder (10%) is the prevailing crop (Amt für Statistik Berlin-Brandenburg, 2021; Wolff and Lakes, 2020). Historical reconfiguration and the ongoing rural shrinkage in the agricultural landscapes affected society (Beetz et al., 2008; Reyer et al., 2012). Increasingly large farms with an average size of 238 ha, which is about four times higher than the national average, are characteristic for this federal state (White and Roy, 2015) and is exceeded by the farms of the regional farmer network. Farms tend to be highly mechanized with labour force of only 1.7 persons per 100 ha (Gutzler et al., 2015). Farmers face increasing legal limitations e.g. for pesticide usage (European Commission, 2020). The dominance of winter crops causes increasing problems with weeds adapted to autumn sowing which are difficult to control (Steinmann and Dobers, 2013). Crop rotations are winter cereal-dominated, a typical rotation is winter oilseed rape – winter wheat – winter barley (Jänicke et al., 2022). Winter oilseed rape has a relatively high pesticide treatment frequency index compared to other crops (Table 1). The pesticide treatment frequency index is the product dose used by the farmer divided by the reference dose, and considers reduced application rates and partial area treatments, where each pesticide product is counted

Table 1
Treatment frequency index for number of pesticide applications for different winter crops and selected years at the national, regional and farm level.

	Treatment frequency index			
	Farm average (2017–2019)*	National German average (2019)	National German average (2020)	CEPI A (2017)**
Wheat	4.8	5.3	4.6	6.1
Barley	4.4	4.2	3.9	4.5
Rye	3.3	3.9	–	–
Oilseed rape	7.5	7.5	6.4	7.9

* Average values include growth regulators and were calculated based on applications in the sole cropped field before patchCROP was implemented.

** Cluster for the regional survey of plant protection intensity including Mecklenburg-Vorpommern and Brandenburg state in North-East Germany (Dachbrodt-Saaydeh et al., 2021).

separately in case of tank mixtures (Nause et al., 2021). The inclusion of spring-sown crops is known to disrupt weed cycles (Melander et al., 2013), but farmers in the region see relatively few options for growing spring crops economically besides maize and sunflower. While grain legumes, especially narrow-leafed lupine and soybean are potential alternatives, market access is limited and prices are often low in conventional farming (Notz et al., 2023).

Good agricultural practices (GAP) came along with changing fertilization regulations to decrease nitrogen (N) surpluses and to minimize leaching losses in Germany (Kühling et al., 2021; Löw et al., 2021). Farmers in our network were concerned about N losses especially since fertilizer prices have increased dramatically during crises in 2022. Despite a minor global increase in N use efficiency over the last two decades (Omara et al., 2019; Udvardi et al., 2021), limited adoption of precision agriculture technologies, e.g. the use of digital tools like sensor-based N application (Chmelíková et al., 2021), among European farmers persists due to economic barriers (Barnes et al., 2019). In our network at least some farmers use precision technologies for demand-oriented N fertilization and apply management zones.

The increasing frequency of weather extremes like prolonged droughts and high temperatures are a major causes for yield fluctuations in Brandenburg and Germany (Döring and Reckling, 2018). Farmers are therefore searching for alternative cropping systems to better cope with climate change to increase cropping system resilience and farming economy (Hertel et al., 2021).

3.2. Explore hypotheses and on-farm partner to conduct the experiment

3.2.1. Formulation of hypotheses before the design of the experiment

While the overall hypothesis ("Diversification of agricultural landscapes achieves different sustainability goals") was formulated by scientists before the onset of the experiment (Fig. 1 "Hypothesis formulation"), the discussion with scientists and farmers led to the following more specific hypotheses and quantitative goals (Fig. 1 "Explore-Identify goals"):

1. *Diversified fields increase the productivity of agricultural landscapes in the long-term (moderate gains in crop yield compared to conventional farming) and thus, improve the cropping system resilience by increasing ecosystem services delivery compared to sole cropping.* This hypothesis is based on the fact that smaller fields provide biodiversity-mediated and yield-enhancing ecosystem services to crops (pollination, biological pest control) due to increased edge density by field borders (Clough et al., 2020; Martin et al., 2019) and that technology-driven management practices can anticipate heterogeneous soil conditions for precision conservation (Knapp et al., 2023). Site-specific allocated crops in patches comprise different rooting depths, thus varying in water and nutrient demands, which in combination could positively affect water storage capacity, soil fertility and carbon sequestration. In this way, resource use efficiency could be improved by saving up to 40% of additional N-fertilizer or by water usage reduction up to 25% (Kumar et al., 2020).
2. *A substantial reduction of pesticides of up to 50% by 2023 is feasible without substantial yield losses through crop diversification, in particular through diversified crop rotations, replacement of chemical with mechanical weeding, consideration of field heterogeneity, integration of structural field elements and targeted crop monitoring.* This hypothesis is based on the assumption that diversification measures will lead to a reduction of pest pressure, outbreak of harmful diseases and weed pressure through the before mentioned synergies of diversified land use patterns and landscape elements like flower strips (Ratnadass et al., 2012). Higher yields of 10% were found close to flower strips, which was attributed to indirect benefits from pest control (Tschumi et al., 2016). Extended crop rotations and crop interactions between patches, and the option to use automated weeding robots further decrease herbicide applications (Machleb et al., 2020; Talaviya et al., 2020).
3. *Autonomous light-weight agricultural machinery will improve the practicability to manage smaller and diversified fields and decrease the labour and input costs of their management in the next decades.* The market share of supervised autonomous machines is forecasted to significantly increase over 80% by 2045 (Dörr et al., 2019). Advances in the use of autonomous field robots could reduce the risk of soil compaction by current machinery (Shah et al., 2017), reduce costs and working time (Lowenberg-DeBoer et al., 2021).

3.2.2. Search for suitable on-farm partners

After the formulation of quantifiable aims derived from our hypotheses, several meetings with three well-known and interested, regional farms were scheduled to discuss the possibilities of a long-term landscape experiment where patch cropping could be realized with farm owned machinery. All farms belong to the regional farmer network. Important decision factors to select for suitability of the agricultural farm were the distance to ZALFs research facilities, the ownership structures of fields, the mechanization level, motivation and long-term commitment. The farm "Komturei Lietzen" was selected, which has a total arable area of about 2000 ha, runs cash crop production and is equipped for precision agriculture (Fig. 1 "Farm & field identification"). The farm implemented permanent machine traffic lines and applies site-specific management for mineral N fertilization, liming and organic fertilization since 2007/08 and uses variable seeding densities since 2018/19. Relevant farm-specific topics and required solutions stated by the farm managers include the focus on improved fertilization management, rotation changes by inclusion of legumes (soybean and narrow-leafed lupine), reduced and flexible strategies to reduce pesticides, creation of smaller fields (or management zones) for precision farming, practicability tests for field robotics and other digital technologies. Furthermore, the farm is intrinsically motivated to collaborate because of the expected positive perception in society caused by increasing cultural ecosystem service and has a long-standing cooperation with ZALF due to other on-farm projects (Fig. 1 "Long-term cooperation"; Joschko et al., 2012).

As a consequence of the agreement between the farm and the research institute, follow-up meetings were held with the farm managers to co-design patchCROP using a dynamic and iterative DEED approach (Fig. 1). A multidisciplinary team of scientists worked together with the on-farm actors to collaboratively discuss and realize innovations on e.g. crop rotation, selection of cover crops, size of flower strips and pesticide reduction strategies to combine technological and institutional innovations as described in Botha et al. (2017). To select the adequate field for the landscape experiment, maps of surrounding fields that belong to the farm were analysed and checked for heterogeneous soil attributes using the German soil fertility index.

3.3. Design of the landscape experiment

This chapter describes the experimental set-up and initial measures for crop diversification and pesticide reduction strategies in the landscape experiment.

3.3.1. Cluster analysis for patch creation

Existing data were provided by the farm to carry out the experimental design on the selected 70 ha field. Georeferenced data of the soil fertility index, multi-year yield maps, proximal sensed data sets of electrical bulk resistivity measured by the GEOPHILUS system (Lueck and Ruehlmann, 2013) and soil sample analysis for texture and soil organic carbon (SOC) were used for spatial heterogeneity analyses at the field scale (Fig. 2). Relative yield was calculated from yield maps generated by combine harvesters over nine years (2011–2019, Table 2) with prior removal of erroneous data points (Donat et al., 2022). A cluster analysis was conducted to divide the field into smaller homogenous field units, designated as patches. For this, georeferenced data were clustered into two groups (cluster centre A and cluster centre B) using an unsupervised Fuzzy C-means clustering algorithm (Bezdek, 1981), which is implemented in the Scikit-Fuzzy package (Python Team, 2016). Patches with continuous class membership values of cluster centre A with values >0.5 were categorized into Cluster group class one comprising low yield potential (Fig. 2C). Patches with values <0.5 were categorized into Cluster group class two of high yield potential (Fig. 2D). A details workflow and independent cross validation for the clustering procedure can be found in Donat et al. (2022). Patches of the same yield potential consist of a variable number of N sub-patches. To agree on the most suitable patch size, technical feasibility with available agricultural machinery as well as knowledge from ecological studies on minimum

Table 2
Mean values (+standard deviation) of yearly relative yields compared to the average standard yield of the field per crop and year (derived from yield maps) and different soil attributes of the two cluster group classes.

Attributes	Low yield potential	High yield potential
Mean relative yield [%]		
Winter rye 2011	71.1 (24.5)	114.6 (22.4)
Oilseed rape 2012	75.1 (20.1)	114.3 (11.5)
Winter rye 2013	90.8 (8.7)	102.9 (6.9)
Winter rye 2014	86.6 (4.6)	106.5 (10.3)
Oilseed rape 2015	53.9 (18.8)	121.6 (14.1)
Winter rye 2016	65.6 (10.0)	115.0 (13.9)
Winter rye 2017	65.5 (13.0)	119.8 (17.0)
Oilseed rape 2018	76.5 (19.4)	118.2 (13.0)
Winter rye 2019	72.2 (10.5)	112.9 (13.6)
Electrical bulk resistivity (0–25 cm) [Ohm m]	438.9 (63.8)	182.8 (54.2)
Clay (%)*	7.5 (1.08)	9.8 (3.35)
Silt (%)*	10.9 (2.44)	21.6 (4.62)
Sand (%)*	81.6 (2.49)	68.7 (5.52)
TOC_%*	0.8 (0.11)	0.9 (0.10)
Soil fertility index	21.5 (4.3)	38.5 (4.5)

* derived from 32 samples used for re-calibration of Geophilus proximal soil map.

patch size were considered. We decided on patches with an edge length of 72 m arranged as square polygons, which corresponds to twice the maximum working width of 36 m used by the farms' crop protection sprayer (Fig. 1 "Co-design experiment-Design Experimental set-up)". The patches are parallel to the farmer's permanent traffic lanes, which allow for controlled traffic farming. High yield potential patches showed

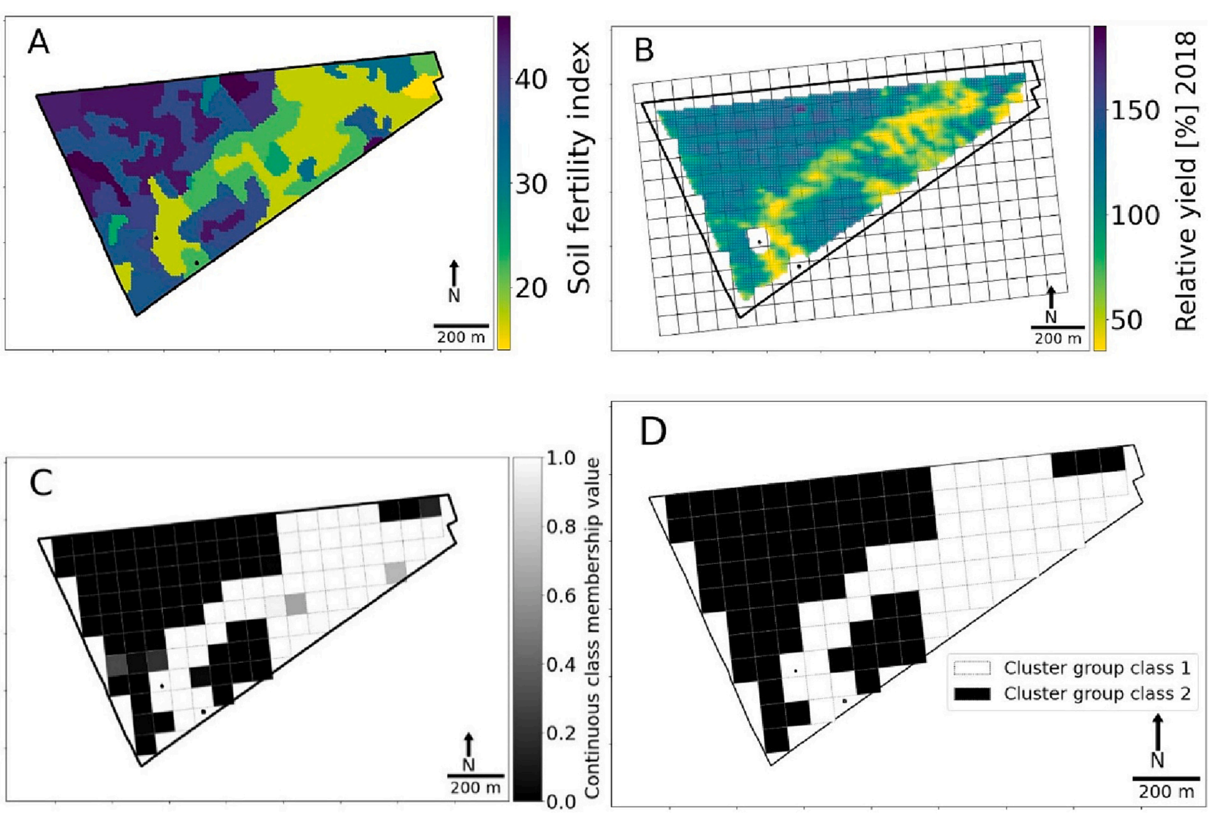


Fig. 2. Spatial layout of soil attributes, relative yield and results of the cluster analyses: (A) Soil fertility index 'Ackerzahl' visualizes and allows comparison of the productivity of arable sites with possible values from 0 to 100, (B) interpolated relative yield in [%] of oilseed rape in 2018, (C) visualization of the continuous class membership values of cluster centre A 'low yield potential' with values from zero to one – if patches have a value >0.5, they will be assigned to the cluster group class 1 'low yield potential' and (D) patches with their corresponding cluster group class - patches visualized in white show low yield potential, patches visualized in black show a high yield potential.

higher relative crop yields over nine years and contained higher SOC, silt and clay content in the top soil (Table 2).

The outcome of the cluster analysis defined the experimental design for the landscape experiment comprising newly arranged, site-specific small structured fields located in two different yield potential zones and blocked in three different land use intensities (Fig. 3), physically implemented in March 2020.

3.3.2. Site-specific crop rotations

Five-year site-specific crop rotations were selected for each high and low yield potential zone (Table 3). Crops were selected depending on the general resource requirements (spatial and temporal niche differentiation, see Pearman et al., 2008), current crop cultivation choices in the area, and nutritional demands of each of the selected crop species. Both crop rotations were co-designed based on expert knowledge, (economical) farm preference and crop rotation restrictions following Reckling et al. (2016).

3.3.3. Field size

The effect of field size is evaluated at the landscape scale: Patches of ~0.5 ha (72 × 72 m) are compared with 50–100 ha large sole cropped reference fields. Multi-annual yield maps were available for the reference fields and were used to cluster them similarly into high and low yield potential zones as described above. From this, one easily accessible area was selected with similar site and soil properties to be comparable with those in the patches. The areas in reference fields had the same initial size of 72 × 72 m and were divided to establish sub-plots of conventional and reduced chemical-synthetic pesticide applications (termed subsequently land use intensity, Fig. 4). Because the entire reference field, which surrounds the reduced sub-plot, is managed with commercial pesticides, a comparability to reduced patches is limited and

Table 3
Five-year crop rotation for each yield potential zone (CC = cover crop before the main crop).

Yield potential	1st year	2nd year	3rd year	4th year	5th year
High	Oilseed rape	Barley	CC-soybean	CC-maize	Wheat
Low	CC-sunflower	Oats	CC-maize	Lupine	Rye

a pest dilution effect is assumed (Dovydaitis et al., 2024). Overall, 760 ha of surrounding fields have been involved in the sampling and monitoring activities so far, including plant and soil samplings, biodiversity assessment and remote and proximal sensing. Thus, the total experimental area covers ~830 ha and serves for agricultural landscape upscaling, contouring the landscape experimentation scale (Fig. 4). Reference fields are managed commercially with the farm-based crop rotation and do not correspond to the crop rotation of the patches, but still serve for valid system comparison (Derpsch et al., 2014; Veldkamp et al., 2001). For certain crops as e.g. winter oats, no reference fields were available each year as they are not part of the farmer's portfolio.

3.3.4. Land use intensity

Land use intensity corresponds to sustainable intensification approaches aiming at the reduction of chemical-synthetic pesticides but maintaining outputs. Positive synergies between the environment, plants and soil built up over time are expected through small-scale diversification and flower strips (Hatt et al., 2017; Holland et al., 2016; Marshall et al., 2006; Raatz et al., 2019; Tschumi et al., 2016).

The first land use intensity comprises business as usual with

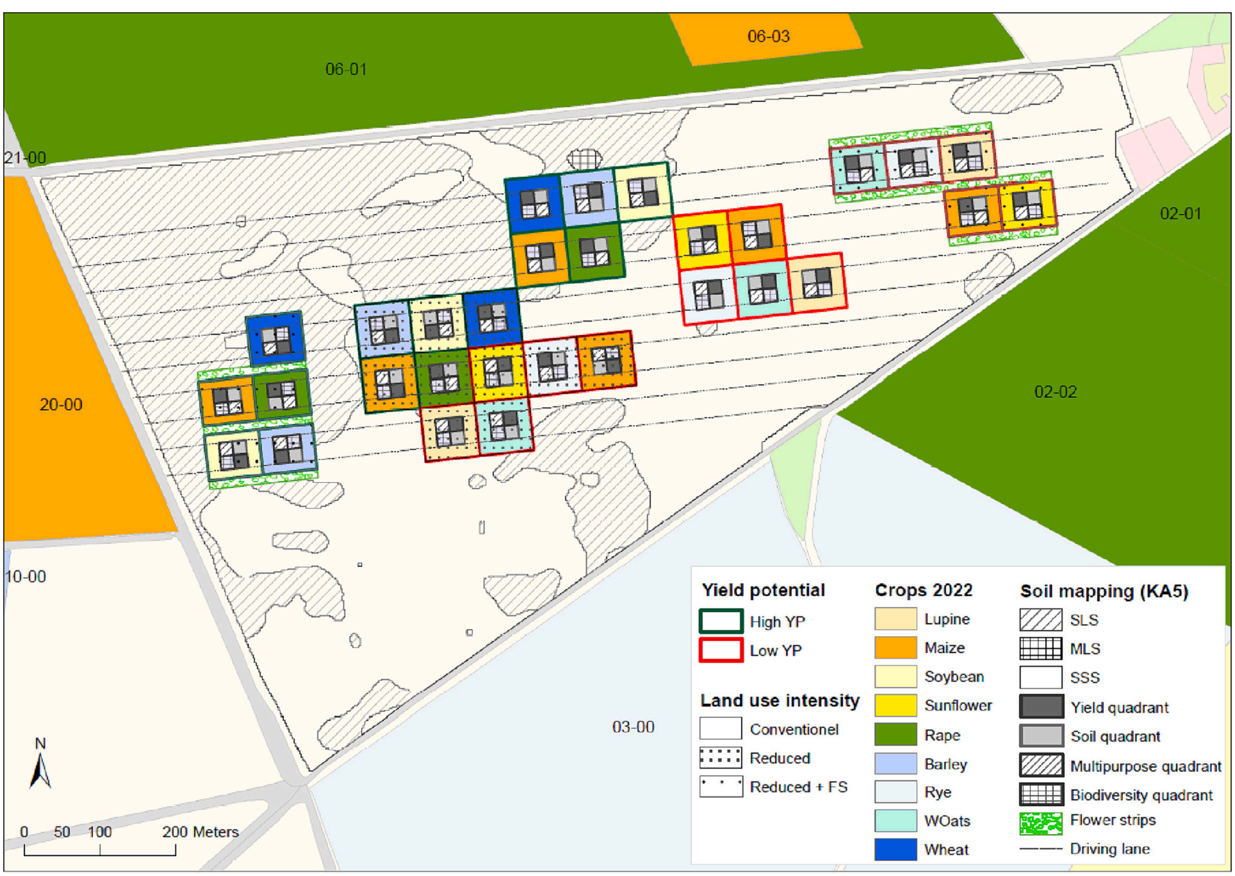


Fig. 3. Experimental layout of patchCROP in the cropping cycle 2022 (YP-yield potential, FS-flower strips, SLS-slightly loamy sand, MLS-medium loamy sand, SSS-slightly silty sand, KA5-soil map (Bodenkundliche Kartierung KA5 in Sponagel, 2005).

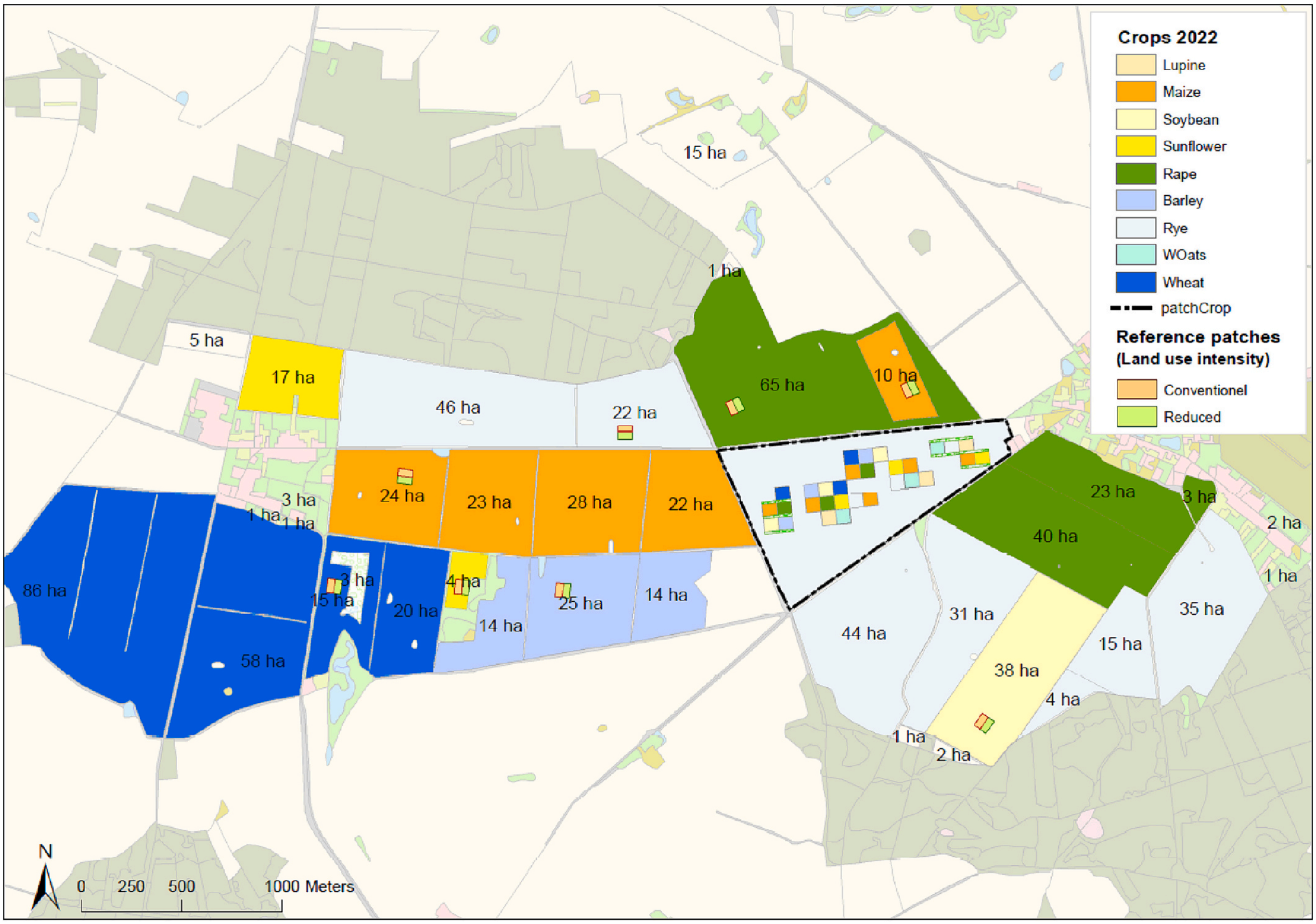


Fig. 4. Reference patches of patchCROP within the surrounding agricultural landscape in the cropping cycle 2022 (Numbers indicate field size in ha, WOats-Winter oats).

conventional pesticide application according to the farmer's perception and integrated farming guidelines. The second land use intensity uses situation- and crop-specific approaches to reduce pesticides based on control thresholds. Land use intensity three applies the same reduction principles as the latter but counts with additional perennial flower strips of 12 m width at two sides of the patches (see below details on flower strips). The daily decision of necessary pesticide applications (type, concentration, combination) in the second and third land use intensity is based on weekly monitoring of weed, pest and disease pressure conducted by experts of the Federal Research Centre for Cultivated Plants (Julius-Kühn Institute, JKI) and ZALF scientists, the use of control thresholds for integrated crop protection and decision support systems (Barzman et al., 2015). Additionally, non-chemical methods such as mechanical weed control are applied with harrowing and hoeing to replace herbicides in spring crops. An autonomous weeding robot (Naio Oz) is tested to replace large machinery in maize.

The overall strategy to reduce chemical-synthetic pesticides in land use intensity two and three is driven by regular exchange and guidance though JKI. In the consolidation phase (Fig. 1), co-design and co-innovation approaches for the field management are carried out bi-annually between JKI, ZALF and the farm to assess critical points and to conduct recorded in-depth discussions (similar to Dogliotti et al., 2014). Discussion points are collected, listed and provided before debating them with the project actors (two farm managers, JKI and ZALF scientists, ZALF research station head, advisor of landscape preservation society; Fig. 1 "JKI workshop"). The decisions on pesticide reduction strategies and their implementation level are discoursed and adjusted until an agreement is reached. Available machinery (e.g. for mechanical weeding), political guidelines (e.g. flower strip composition) and market driven factors (availability and delivery times of certain pesticide products) are taken into consideration to decide on suitable and feasible pesticide reduction strategies. Certain project targets for pesticide reduction were set and aligned with the EU Green Deal (European Commission, 2020) to be reached after three and five years after the experiment was initialised and were based on averages of the current treatment frequency index in Germany (Table 1). The success of implemented pesticide reduction strategies is monitored with the treatment frequency index which ideally is averaged over the five-year crop rotation (Lamichhane et al., 2016).

3.3.5. *Perennial flower strips*

In land use intensity three, flower strips of 12 m width were implemented at two sides of each of the 10 patches. A perennial mixture of six cultivable plant species and 28 wildflower species was selected for dry habitats as recommended by the Brandenburg state ministry of agriculture. Perennial flower strips were mulched in autumn as three 2 m wide strips and mulched strips were re-sown with an annual mixture of 17 species in 2021 and 10 species in 2022 in spring to increase and regenerate the flowering effect. The remaining two 3 m wide strips remain intact and provide overwintering habitat with soil cover and woody stems of some species.

3.3.6. *Patch arrangement for sampling and monitoring*

patchCROP consists of a total of 30 patches (Appendix 1 for detailed overview of each patch and its treatment combination (yield potential zone, land use intensity, crop rotation)) without spatial replicates. The remaining field area around the patches was planted annually with rye, being a self-compatible, modest and less prominent flowering crop, which was supposed to have minor interactions within the patchy setting. In each cropping cycle, up to nine reference patches (except for winter oats) have been implemented in surrounding fields that are split into 18 reference areas for conventional and reduced pesticide management (Fig. 4). Patches do not have border areas and adjoin each other (share the same edge), which should facilitate patch interaction in terms of biodiversity. On the other hand, the design impedes smooth field movement for measurements and large-scale machinery. Therefore, an undisturbed core sampling area of 36 × 36 m (in between permanent traffic lanes) was established in the centre of each patch which avoids the headland area and omits conventional machinery impact. This area is further divided into four sampling quadrants (18 × 18 m, Fig. 5) with comprehensive monitoring and sampling activities as follows:

I. Yield quadrant: grain yield, leaf area index (LAI), normalized difference vegetation index (NDVI), biomass, phenological stages.
II. Soil quadrant: deep and shallow soil sampling, in-situ physical, chemical and biological soil measurements, LoRa-based soil sensor system.
III. Biodiversity quadrant: biodiversity monitoring, trap installation, pest populations, weed scoring.
IV. Multipurpose quadrant: on-time or destructive measurements.

Machine access and headland turns are conducted on the remaining area outside the core area as the higher number of machinery traffic on the patches is reducing plant stands and thus yield, and affects soil properties like bulk density. However, edge and border effects can be assessed for specific research questions (e.g. resource use efficiency, photosynthesis activity, nitrogen dynamics, short-distance niche differentiation for insects) by means of sampling transects from an intact patch edge towards the patch centre, avoiding the headland area of each patch. We emphasize that the vision of patchCROP includes the use of currently still limited available small autonomous field machinery, which would avoid the negative drawbacks of large conventional machinery at the present time.

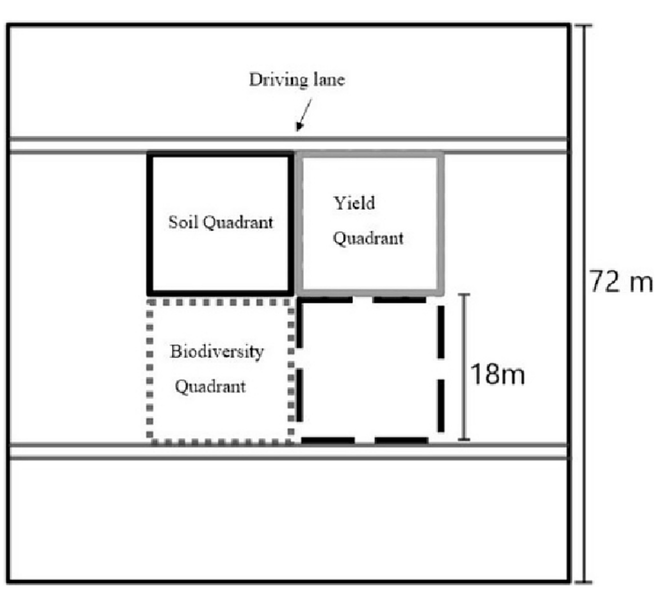


Fig. 5. Schematic design of a patch depicting its dimensions and the permanent sampling and measurement quadrants (core area).

3.3.7. *Multidisciplinary data collection*

A comprehensive data management plan (DMP) was developed during the consolidation phase of the experiment, which is updated once a year by all academic project participants and summarizes the description (metadata) and generation (methodology) of data (Fig. 1 "DMP").

Data are collected at four different scales: in quadrants (Fig. 5), patches, the entire field and in the surrounding agricultural landscape (Table 4). This allows, for example, to link crop productivity with its implications for bird diversity and ground beetle abundance or to associate soil fertility with yield stability, crop quality and pest pressure. This landscape perspective provides the possibility to develop multi-causality concepts and interacting theories for land-use interdependencies and landscape research that are evaluated from different points of view by ecologists, agronomists, soil scientists and economists (Gaba et al., 2015; Kernecker et al., 2022; Pereponova et al., 2023b). One experimental novelty of patchCROP is the extension of integrated crop protection strategies towards the landscape context, incorporating aspects of increasing diversification (e.g. Kremen et al., 2012) and decreasing pesticide use (e.g. Frische et al., 2018). The collection of numerous data, especially through Internet of Things originating from the LoRa-based soil sensor system (Scholz et al., 2023; Tzounis et al., 2017) or digital yellow traps (Dovydaitis et al., 2024), serves to apply new statistical approaches and artificial intelligence looking for unknown relations and can be seen as the next step of using big data to develop sustainable cropping systems (Wolfert et al., 2017).

The platform character allows students, practitioners, and researchers in- and outside the institute to use this experimental research infrastructure in an integrative way for multidisciplinary study purposes which is complemented by a basic monitoring program offered to the users (weather, drone, yield, biomass, basic soil properties, etc.). A sample archive for biomass, grain and soil samples was established, providing the opportunity to answer new research questions with new methodological approaches in the future (Ayres, 2019). For improved communication during the consolidation and implementation phase of the landscape experiment, ZALF has developed the patchCROP "Traffic lights", a web browser application to communicate and visualize daily activities (field operations, measurement and sampling campaigns, media visits, field tours) which significantly improved the occupational safety of the experimental platform since 2021 (Fig. 1 "Data collection").

4. Co-design of the management measures for diversification and pesticide reduction

4.1. *Describe and explain the functioning of the landscape experiment*

The description and exploration of the patchCROP experiment (2nd DEED cycle, Fig. 1) revealed strengths, weaknesses, opportunities and threats that were compiled with scientists (Table 5) and two farm managers of the selected farm (Table 6). The first (co-) design cycle segues into the second co-design cycle as the management of the landscape experiment is permanently and frequently tested and evaluated with project actors at all levels of interaction. The following section summarizes the outcome of the two SWOT analyses (method explained in chapter 2.2) for both groups and discusses substantiating literature, connection points and potential solutions to reinitiate the DEED cycle a third time in future ("Iterative feedback loops", compare Fig. 1).

4.1.1. *Strengths of the patchCROP experimental platform*

The value of an on-farm experimental platform like patchCROP is the provision of a scientific infrastructure for crop diversification combined with upcoming technologies to close the gap between farmers and science. The intra- and interinstitutional participation of scientists and experts resulted in a broad multidisciplinary data acquisition to answer multidisciplinary research questions (Table 5). Hence, it collects and provides data for future and further analyses of topics and research

Table 4
Current data collection and acquisition in patchCROP sorted by discipline and scale.

Scale	Agronomy	Soil Science	Biodiversity	Crop protection	Operational data
Quadrant & Patch*	Plant counts	Soil moisture	*Sitona* beetle abundance	Digital yellow traps for oilseed rape pests	Planting (density, variety, row distance)
	Plant height	Soil temperature	Wildflower species in flower strips	Pest incidence	Fertilization (dose, type)
	Plant stage (BBCH)	Electrical conductivity		Pathogen incidence	Pesticides (type, concentration)
	NDVI	Organic matter composition		Scoring of treatment success	Tillage
	LAI	Earthworm abundance			Work hours
	Biomass (+N, P, K)	Microbial activity			
	Harvest (+N, P, K)	Nutrients (mineral N, total N, SOC (POM and MAOM C&N), P, K, Mg)			
	Straw (+N, P, K)	Soil pH			
	Thousand kernel weight	Carbonates			
	Harvest index	Infiltration			
	Number of spikes	Bulk density			
	Photosynthesis rates	Texture			
	Yield maps	Visual Evaluation of Soil Structure			
	Predicted crop yield	Soil aggregate distribution (wet& dry)			
Field	UAV-RGB	Erosion elevation model			Precipitation
	UAV-multispectral	EM38- apparent electrical conductivity			Air temperature
	UAV-thermal	Gamma-Spectrometer			Air moisture
		X-Ray fluorescence			Wind speed
					Solar radiation
					Photosynthetically active radiation
Landscape	Cropping system model output variables (SIMPLACE)	Veris- apparent electrical conductivity (ECa), pH, diffuse reflectance in the near infrared (NIR)	Ground beetle abundance & species	Weed incidence	Digital elevation model
	Satellite- Sentinel NDVI	Geophilus- electrical bulk resistivity	Spider abundance & species		Crop rotation plan
	Satellite- PlanetScope (8 bands)	Reichsbodenschätzung (German soil value number)	Bird abundance and species		

* Patch scale includes sampling and monitoring in reference patches of surrounding fields; LAI- leaf area index, NDVI-normalized difference vegetation index, N-Nitrogen, P-Phosphorus, K-Potassium, UAV-unmanned air vehicle, SOC-Soil organic carbon, Mg- Magnesium).

questions that are not considered yet, for example economic analysis of new field arrangements, societal acceptance or the costs of robotics.

Crop diversity was increased in the rotation from 4 to 9 crops over the last 16 years in one single field. Before patchCROP was implemented, this field was cropped five years with oilseed rape, nine years with rye and one year each with wheat and barley. Additionally, diverse information for currently less important crops like lupin, soybean, sunflower and winter oat are collected within the current rotation that may not be the focus in other field experiments (Table 3). The patchCROP arrangement significantly increased field edge density from 3914 m of the original 70 ha field to 7464 m between 30 patches and six flower strips which was reported frequently as driving factor for supporting biodiversity (Hass et al., 2019, 2018; Larsen and Noack, 2020).

Frequent transfer activities for and with society (field days, field tours, citizen question sessions, information signs for public, media reports and the website www.landschaftslabor-patchcrop.de rise awareness and visibility for diversified agricultural landscapes (Fig. 1 "Transfer"). The reliable and trustworthy collaboration with the farm managers is the main prerequisite as the project relies on optimal crop management and the provision of relevant operational and scientific data. The project team is experiencing a continuous and iterative co-learning and evaluation process regarding successful or failed strategies, tools and implementations like the dynamic approach of pesticide reduction strategies, the selection of crop species in the five-year crop rotation or the determination of the flower strip composition (Table 6). The long-term character of patchCROP enables capacity building, trust between project participants and may lead to real sustainability transitions as happed in Rossing et al. (2021).

4.1.2. *Weaknesses of the patchCROP experimental platform*

patchCROP does not have a conventional experimentation design with fixed treatments, randomisation and replication. Hence, each patch represents one experimental unit with a unique combination of factors (yield potential, crop, and land use intensity) without replicates. To reach a minimum number of replications for sampling and measurements, pseudo-replicate design is applied by dividing sampling quadrants into strips of three or six and by selecting sampling sites randomly within these sub-plots. Recently, data collected in patchCROP have been statistically evaluated using general linear models, soil erosion and agroecosystem modelling or principal component analysis (Dovydaitis et al., 2024; Hernández-Ochoa et al., 2024; Koch et al., 2023; Scholz et al., 2023). We are aware of potential challenges that landscape experiments induce due to the ambitious task to quantitatively delineate different effects (Table 5). Nevertheless, replication of such a complex experiment in a different landscape will likely implicate changes in several factors (crop rotation, strategies for pesticide reduction, ect.) in contrast to field experiments where typically only soil conditions vary among replicates. Contrasting to field experiments, landscape experiments do not exclude heterogeneity, but integrate and analyse it. Furthermore, landscape experiments present a non-traditional research method to observe numerous processes that interact at different scales in a complex way (as do agricultural systems) and therefore could reduce the risk to disregard unexpected cause-effect relationships (Pereponova et al., 2023a). Finally, the co-design process resulted in a tailored experimental design for a specific region and a concrete group of farmers which is unlikely to be valid and transferable to other regions.

The patch size was determined by the size of available agricultural machinery of 36 m working width and is sustained over the length of the experiment. While the smallest units of homogenous patches for spatial diversification might be much smaller, it cannot be adapted in this experiment (Table 5). Also, the patches were selected as rectangular polygons with relatively homogenous conditions which do not represent

Table 5
SWOT analysis conducted with scientists.

Strengths		Weaknesses	
Process understanding	Demonstrate spatial and temporal crop diversification combined with new technologies simultaneously	*Data collection & analysis*	High crop diversity and landscape scale approach increase data collection efforts
	Identify drivers for the implementation of smaller field sizes		Challenging analysis and interpretation of spatio-temporal data without replication
	Support upscaling of processes from the field to the landscape scale		Sustainability and socio-economic research questions still limited
	Provide information on spatial variability of soil health indicators		Biodiversity measurements still underrepresented and very costly
	Significant structural and crop diversity increase at the field scale		Multidisciplinary measurements at the landscape scale still limited
Experimental approach & co-design	Test new field arrangements in reality	*Resources*	High trial maintenance costs
	Optimize the design and feasibility of the living lab approach with several stakeholders		High investment costs for novel technologies and autonomous field robotics
	Identify practicability and farmers' acceptance of new practices		Lack of resources to match measurements e.g. UAV with field data
	Platform to close the gab among and between scientists and farmers		Limited development of digitalized methods for ecosystem services and biodiversity assessments
Big data & interdisciplinary platform	Increasing understanding of multilevel effects through multi- and transdisciplinary research activities	*Upscaling & transferability*	High landscape heterogeneity increases uncertainty affecting model upscaling
	Platform to involve and train young researchers and scientists		Adaptation and immediate practical use by farmers are delayed
	Support collaboration within and across research organisations		Despite "small patches" high soil heterogeneity within patches
	Intensive data collection, storage of data and soil/plant samples for future research questions and methods	*Research approach*	Difficult to keep transparency in research highlights and future research activities due to different languages among discipline/ stakeholders
	Use of innovative technologies and methods/tools for data collection		Institutional decisions vs. participatory involvement reduces motivation
Outreach	High visibility and media attention		Narrow co-design approach and limitations to implement at bigger scale
	Transfer activities with farmers and society		Landscape dependent, e.g. no inclusion of organic crop management
Opportunities		**Threats**	
Scientific output	Integrated assessment combining crop development, soil processes, biodiversity, and hydrology	*Maintenance & duration*	Long-term commitment & financing of experimental platform and infrastructure
	Improved and systemic understanding of ecosystem services		Vague temporal perspective for the experiment due to funding uncertainty
	Systematic improvement of efficient use of resources and advances in sustainable development		Risk of early project termination before an added value has been achieved
	Using models to integrate proxy for upscaling related to soil processes or biodiversity		Available third-party funding and additional projects
	Optimization of field arrangements (patch size, geometry) through spatial and temporal diversification		Acquisition of trained and qualified employees for a longer period
Scope	Strong connection to agricultural practice enables evaluation of applicability of research ideas	*Transfer*	Greater crop diversification is limited by availability of suitable, small machines
	Incentives for farmers to implement patchCROP through agri-environmental measures and green deal policies		No realistic assessment of small-scale field diversification is possible with current machinery
	Community outreach to neighbouring municipalities		Lack of extension capacity within and beyond the experimental platform.
	Experimental platform with diverse subprojects has potential for scientific replication in other regions and countries		Heterogeneity in soil, geology and land use impedes transferability to other regions
	Digital tools and autonomous field robots are evaluated in the experiment to be used in other contexts	*Complexity*	Experimental design unsuitable for conventional statistical analysis
			Lacking big data approaches for high-dimensional, heterogeneous data sets

real landscape conditions consisting of natural polygons or spots (Wegener et al., 2019). From the farmers' perspective, the small operable patch area generates concentrated zones of overdriving, soil compaction and reduced plant stands, especially in the patch corners and edges (Table 6) as adequate smaller machinery is not available.

4.1.3. Opportunities for the patchCROP experimental platform

For scientists, the most important opportunity arises from the integrated assessment of landscape functionality in terms of crop performance, soil processes, biodiversity, hydrology and resource use. The upscaling from field to regional level can be possible by the use of crop simulation models integrated with other technologies such as remote sensing (Manivasagam and Rozenstein, 2020; Morell et al., 2016). Although certain crop models are able to simulate a range of ecosystem services, they need to be improved for other processes such as modelling biodiversity dynamics, crop-crop interactions, pest-crop interactions, and impacts of certain landscape elements (Hernández-Ochoa et al., 2022).

In line with the initial hypothesis (chapter 3.2.1), the European research alliance "Towards pesticide-free agriculture" was launched in 2020 and consists of 34 members from 20 countries to promote the reduction of chemical-synthetic pesticide applications with the aim to maintain or increase biodiversity (Jacquet et al., 2022). In science and politics, there is a strong interest towards the greening of agriculture through pesticide reduction and ecosystem service increase (Jacquet et al., 2022), which could be optimally translated to an ecological modernisation of agriculture, using modern technologies encompassing to the landscape scale (Basso, 2021).

We encourage the development of smart and tailored field interventions to fill the gap of integrated, multipurpose solutions of digital

Table 6
SWOT analysis conducted with farm managers.

Strengths		Weaknesses	
Knowledge gain	First-hand knowledge from scientific experts	*Field management*	Large machines on a small patch area cannot reach their full efficiency and have complicated field routes
	Increased knowledge and experience with the cultivation of new crops like sunflower or soybean		Patch corners get weedy and marginal areas become larger over time due to poor accessibility with big machinery
	Increased knowledge on strategies to reduce application of pesticides and experience with mechanical weed control		Plant and soil damage caused by over-driving and headlands in the patch edges
	Continuous skill improvement in planning and organizing tasks for crop management measures like site specific management		Increased soil compaction in the headland areas
Equal partner- ship	Voice to shape relevant research questions for farmers in science	*Commercialization*	Selected crops in patchCROP rotation do not necessarily match economic market trends
	Farmers and research institute are equal partners		Difficult to market “niche” crops grown on small area
Farm progress	Auto-evaluation of the standard farming practice compared to crop management measures applied in patchCROP	*Planning security*	New, “spontaneous” measures to reduce pesticides increase planning uncertainties of additional trial costs
	Agricultural system trial without fixed treatments and rotations, but generally formulated targets for pesticide reduction over 5 years		Need of long-term and more precise agreements on press and media relevant information and dates
Data	Accessibility to collected data, e.g. weather data dashboard or Lora Soil sensor Network, which is used for decisions making on field measures	*Information obligation*	Laborious and time consuming communication with scientists
			Data privacy is a concern as the farmer provides sensitive data to their partners
Opportunities		**Threats**	
Networking	Farm gets pioneering role as scientific partner	*Research outcome*	High visibility of the trial entails great responsibility and caution when communicating the results and the recommendations derived from them
	Expanded networks to industry, scientists, experts		Conclusions from the trial cannot be transferred to other regions
On-farm Transfer	Possibility to carry out new, practice-relevant projects with ZALF and other partners	*Resources*	Inadequate research questions for other farms
	Increased perception of importance of on-farm experimentation		Incalculable costs due to future projects and trial extensions
	High transferability of results to other areas of the farm which are similar to soils & climate		Prone to become robbery target
	Recognition by other farmers	*Field infrastructure*	Soil and crop growth quality of the field is reduced after the end of the trial due to the risk of increased weed pressure and soil compaction
Technology transfer	Uniqueness to serve as platform of new technologies and field robots		Disable time-specific measurement on other field if coincidence with patchCROP work
	Regular field days with robotic demonstrations increase awareness		
Farm economics	Incorporation of new crops into the farm crop rotation extend crop portfolio and decrease risk of crop failure		

interventions for farmers (Fountas et al., 2020). In the future, accessible field robotics may allow to change the size and even patch geometry, which increases their technical feasibility and contributes to sustainable intensification (Wegener et al., 2019). By organizing workshops and promoting the development of prototypes that match with the demand for multipurpose-multicrop robots, we build the link to different components of various technologies for field interventions (like planting, weeding, fertilizing, crop scouting). This is a direct contribution to progress in the practical realization of diversified fields and to improve target variables like ecosystem services and biodiversity, which are still biased using current large farm machinery.

4.1.4. Threats for the patchCROP experimental platform

We remark the high efforts that need to be carried out in landscape experiments, which compared to conventional field trials, require extraordinary financial input for field operations and technical staff, and a long-term commitment from both, researcher and farmer teams (Table 5). The high experimental maintenance costs pose the risk of limited long-term financing of experimental platforms which is one of the principle restrictions for more long-term agricultural research (McRae and Ryan, 1996).

Still, there are limits of digital and smart interventions for sustainable crop protection and diversified cropping systems (Ditzler and Driessen, 2022). The link between fields to landscape scale deserves more attention to make better use of digital technologies. Considerable heterogeneity in soil, geology and land-use could impede the generalization of the results (Table 5). Much will depend on obtaining and selecting relevant data that can be used for landscape upscaling coming from targeted landscape experiments (Jenerette and Shen, 2012). Data privacy and ownership plays a major role when using farm data and requires regulatory frameworks and transparent data sharing guidelines (van der Burg et al., 2019).

We point out that there were hardly any economic advantages of small-scale field diversification with today's technology (Table 6). To optimize the future use of field robotics, information like optimal patch size and form and maximum affordable price are essential (Lowenberg-DeBoer et al., 2021). The field size and form should be examined for each farm individually and planned according to agro-ecological principles and the availability of sensor-based high-resolution data, which are rarely available in this magnitude. However, we need to consider that cropping systems nowadays and in the past were only a compromise and result of decades of adaptation to the advancing technical development. Fields became larger as machines became bigger and labour became more expensive (Hallam, 1991). In the future, field mechanization should be created based on best fitting sustainable cropping systems when (multi-purpose) field robotics become work effectively, precise and are available at acceptable costs.

4.2. Explore and design adjustments in the management

The designed patchCROP landscape experiment attempts to close an "experimental gap"by linking classical agricultural research approaches based on supervised learning to farmer-based unsupervised learning that supports informed adjustments of the experimental set-up, management activities and measurements. This farmer-based approach is leading to an integration of agronomic and socio-economic factors for systematic problem solving (Maat, 2011). In order to further improve the experimental set-up and maintenance, several communication formats have been implemented after the SWOT analysis. One is the "patchCROP activities and measurements meeting" carried out monthly with documented interactions between researchers, project collaborators (e.g. industry partners) and farmers. Secondly, bi-annual workshops are organized between JKI, the farm and ZALF for problem solving on pesticide reduction strategies for winter and spring crops (Fig. 1 "JKI workshop"). Thirdly, yearly colloquia are offered to present project updates and discuss results (Fig. 1 "Milestone seminar"). This structure of meetings supports an iterative process of describe, explain, explore and design phases (DEED cycle) to continuously adapt the research approach to the changing needs.

5. Perspectives for co-designing agricultural landscapes

For the co-design of the landscape experiment, the DEED cycle was applied twice in this study and a third cycle started that will continue in the future. Several DEED cycles including the characterization of a new state after the re-design of the experiment improved to tailor them further to the specific research and farmer needs (Falconnier et al., 2017). Our operationalization of the DEED approach in a landscape experimental context allowed moving beyond "farmers evaluating and researchers deciding" which options work best (Pircher et al., 2013). The co-learning affected the willingness to experiment with new cropping strategies and crops, encouraged exploration of solutions to overcome site- and farm-specific constraints (Prost et al., 2018) and contributed to farmers' understanding of their own cropping system functioning (Toffolini and Jeuffroy, 2022). According to Toffolini et al. (2017), the agronomists' involvement in such research processes also influences the production of scientific knowledge. As a result, researchers adapt their scientific aims to the farmers' needs while farmers review their goals and means as a result of these interactions (Hazard et al., 2018). Overall, different actors were brought together and a new experimental platform was established for testing new diversification approaches that may be relevant for other parts of Europe as well.

Landscape experiments like patchCROP offer the springboard to create a living laboratory (living lab) through co-innovation and co-development which is dealt with in a future third cycle (Fig. 1 "Co-design landscapes"). Living labs enable the integration of non-technical aspects in technical innovation processes (von Geibler et al., 2014) and involve all relevant actors and stakeholders within a local or regional system (Fig. 1 "Co-design new systems in a landscape full of actors"; Ewert et al., 2023). The concept of living labs relies on the co-creation of sustainable solutions for the respective system (here, agroecosystem) and involves on-farm experimentation in the agricultural context (Steen and van Bueren, 2017; Yousefi and Ewert, 2023).

The implementation phase of the third DEED cycle focuses on the core principles of user (here farmer)-centric innovation, real life experimental set-ups (in on-farm settings) and private-public-people partnerships building up during workshops and field days (McPhee et al., 2021) which cover larger regional scales, for example the districts of the regional farmer network (Fig. 1 "Co-design landscapes"). Thus, the implementation phase frames the living lab approach to reach practical feasibility of diversified cropping systems that integrate concrete technologies for weather, crop, soil, pest and biodiversity monitoring to reach landscape multifunctionality under long-term engagement between researchers and multiple societal actors (Fig. 1 "E: (3) Implementation phase). Recent research initiatives promote the application of the living lab approach in agricultural landscape research to support farming system transformation and enable the inclusion of multiple stakeholders within a larger network (Busse et al., 2023; McPhee et al., 2021; Toffolini et al., 2021).

6. Conclusions

We have shown for the first time how an agricultural landscape experiment can be established and adjusted continuously using an iterative co-design process. We created a platform to explicitly test the effects of spatial and temporal diversification of cropping systems and to explore options of pesticide reduction using traditional and digital technologies within the landscape context.

The patchCROP landscape experiment offers a unique space to experience and assess new questions e.g. the potential of digital technologies including field robotics with a wide range of crops and soil conditions. It provides the scientific framework to obtain systematic measurements of crop production, resource use efficiency as well as biodiversity indicators and ecosystem services delivered from diversified agricultural landscapes.

The DEED cycle served as a framework ensuring dynamic improvement and progress during the project development and will be applied further to scale out diversification approaches into a larger regional living lab context with a larger group of farmers. Experimental platforms like patchCROP provide tailored experimental solutions at the landscapes scale. They should be developed together with relevant actors to reach the highest degree of innovation. In the larger context of agricultural systems transformation of entire regions and countries, co-designed landscape experiments may be considered as essential nucleus for the development of agroecosystem living labs.

Funding

The patchCROP experimental infrastructure is maintained by the Leibniz Centre for Agricultural Landscape Research (ZALF). M.R. was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – 420661662. I.H. has been funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy – EXC 2070-390732324. M.D. has been funded from the Digital Agriculture Knowledge and Information System (DAKIS) Project (031B0729A), financed by the German Federal Ministry of Education and Research (BMBF), K.G. has been funded by BMBF in her Junior Research Group SoilRob, project ID 031B1391.

Ethics approval

Not applicable.

Consent to participate

Not applicable.

Consent for publication

All authors have read and agreed to the published version of the manuscript.

Code availability

Not applicable.

Authors' contributions

Conceptualization: K.G., M.R., F.E.; Methodology: K.G., M.R.; Data handling and analysis: K.G., M.D.; Visualization: K.G., M.D., M.R.; Project administration: K.G., F.E., S.K.; Writing-original draft: K.G.; Review and editing: K.G., M.R., I.H., F.E., M.D., S.K.. All authors read and approved the final manuscript.

CRediT authorship contribution statement

Kathrin Grahmann: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Moritz Reckling:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Ixchel Hernández-Ochoa:** Writing – review & editing, Writing – original draft. **Marco Donat:** Visualization, Formal analysis, Data curation. **Sonoko-Bellingrath-Kimura:** Writing – review & editing, Project administration. **Frank Ewert:** Conceptualization, Funding acquisition, Project administration, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no conflict of interest.

Data availability

The data presented in this study are available on request from the authors.

Acknowledgments

We thank David Caracciolo, Maria Schnaitmann, Robert Zieciak, Felix Erbe, Sybille Jünger, Lars Richter, Sigrid Ehlert, Gerlinde Stange, Christoph Möller and ZALFs team "Experimental station Müncheberg" for field trial maintenance and data collection. We thank Felix Gerlach and Marcel Budras from Komturei Lietzen GmbH for the trial implementation, their permanent contributions and support for trial improvement. We acknowledge the continuous efforts of the team at the Julius Kühn Institute, Silke Dachbrodt-Saaydeh, Jürgen Schwarz, Bettina Klocke and Thomas Kunze. The design and implementation process was additionally supported and driven by ZALF researchers (Michael Glemnitz, Johann Bachinger, Peter Zander, Ruth Ellerbrock, Dietmar Barkusky); by researchers from University of Bonn (Thomas Döring, Thomas Gaiser), and other institutes (Hans-Peter Piepho, University of Hohenheim; Ralf Bloch Hochschule for Nachhaltige Entwicklung, Eberswalde). Figs. 3 and 4 were created by Sigrid Ehlert (ZALF). F.E. acknowledges support from the German Research Foundation under Germany's Excellence Strategy, EXC-2070-390732324 – PhenoRob. K. G. acknowledges support from BMBF for the Junior Research Group SoilRob, project ID 031B1391. We acknowledge the reviewers for dedicating their time and effort to evaluate the manuscript which has greatly contributed to the improvement of our study.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2024.103950.

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