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On-farm implementation of transformative technologies and practices for sustainability transitions in agriculture

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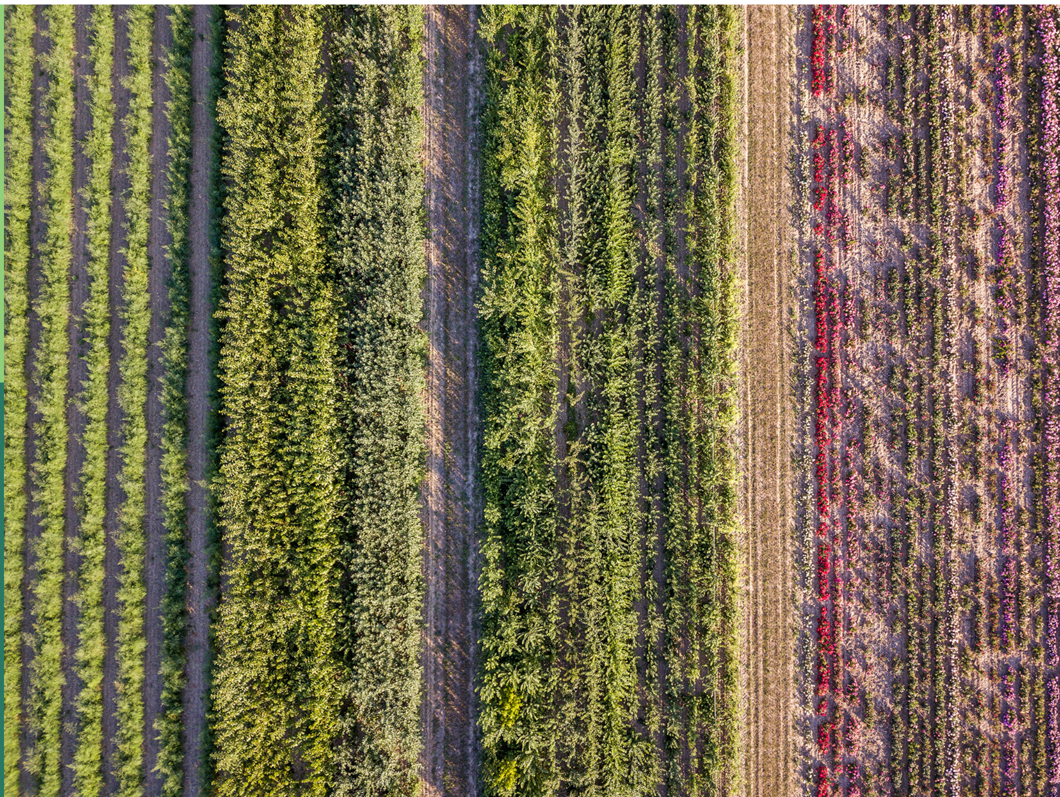
Published in
Frontiers in Sustainable Food Systems



ISSN 1664-8714
ISBN 978-2-8325-6360-1
DOI 10.3389/978-2-8325-6360-1

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On-farm implementation of transformative technologies and practices for sustainability transitions in agriculture

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Citation
Eastwood, C., Ingram, J., Renwick, A., Fielke, S., Edwards, P., Ayre, M., eds. (2025). *On-farm implementation of transformative technologies and practices for sustainability transitions in agriculture*. Lausanne: Frontiers Media SA.
doi: 10.3389/978-2-8325-6360-1

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frontiers | Frontiers in Sustainable Food Systems

TYPE Editorial
PUBLISHED 08 May 2025
DOI 10.3389/fsufs.2025.1616512

OPEN ACCESS

EDITED AND REVIEWED BY
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RECEIVED 23 April 2025
ACCEPTED 24 April 2025
PUBLISHED 08 May 2025

CITATION
Eastwood CR, Edwards JP, Ingram J, Ayre M, Fielke S and Renwick A (2025) Editorial: On-farm implementation of transformative technologies and practices for sustainability transitions in agriculture.
Front. Sustain. Food Syst. 9:1616512.
doi: 10.3389/fsufs.2025.1616512

Editorial: On-farm implementation of transformative technologies and practices for sustainability transitions in agriculture

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KEYWORDS

sustainability, digitalization, agroecology, diversification, uncertainty

Editorial on the Research Topic
On-farm implementation of transformative technologies and practices for sustainability transitions in agriculture

There is increased pressure on agri-food sectors globally to transition to more sustainable food systems (Klerkx and Begemann, 2020). Transformative technology and practices advocated by scholars and policy makers include digitalization and automation (Ingram et al., 2022; Kukk et al., 2022), agroecological systems (Wezel et al., 2020), diversification (Roesch-McNally et al., 2018), de-intensification, local food systems, circularity (Velasco-Muñoz et al., 2022; Bracke et al., 2023), transformative value chains (Mechri et al., 2023), and land-use change for net zero. These practice changes ultimately need to be implemented at a farm scale, but the implications will impact regional and global food systems.

Theories of transformative agricultural technologies and practices are widely researched and modeled. However, greater scholarly focus is required on the farm system level implications, including the positive and negative effects on the livelihoods of those being urged to change (Vermeulen et al., 2018). Transformation can be a complex process that intersects land, livelihoods, and security of the wider food supply system. Moving from theoretical concepts to reality in farming systems can be difficult to implement for farmers due to unforeseen implications (Romera et al., 2020). Better understanding of farmer experiences is needed for effective and viable transformation.

This Research Topic includes nine articles related to innovation processes, land use transitions, roles of advisors, application of agroecological practices, and farmer perspectives in change processes. The research represents regional contexts including Kenya, Australia, the UK, the Netherlands, Ghana, and the Philippines.

Farmers or land managers are at the front line of both sustainability challenges and societal pressure to change approaches to agricultural production. The process of change can involve significant uncertainty and risk, therefore empirical studies of novel practices are vital to provide farmers with evidence and knowledge of what change processes actually involve including associated challenges and benefits. Juventia and van Apeldoorn note that there are limited empirical studies related to diversification using intercropping. Their study evaluated the edge effects of strip cropping in the Netherlands and highlights the importance of practical management considerations when designing crop systems. More broadly, in their research of agroecological design in Kenya, Kuria et al. show that it is vital to understand constraints to agroecological transition that are context-specific, from soil and water constraints to implications of household dynamics. While including farmers in co-design and experimentation is critical to achieving positive change, Stone et al. highlight that this approach will only lead to sustainable transition if integrated in governance frameworks and value chains that support the farm systems. They also note that care is needed to ensure collaboration does not only involve more privileged farmers while excluding those who have the biggest impediments to change.

Dumas et al., in their study of Ghanan agroforestry transitions, highlight the role of blocking mechanisms, such as institutional frameworks with land tenure security, uncertainty related to long-term investments, and lack of financial resources or access to finance of upfront investments. Farmer knowledge, confidence in managing new systems, and negative past experiences are important in such changes. Through a study of an innovative tiller device for Laboy fields in the Philippines, Manalo et al. examined scaling ingredients and highlight that while popular, some components of land practice change may not thrive if specific conditions are not met. They also propose the role of altruism in successful scaling, an important insight deserving further research attention. Acceleration and sustainable scaling of agroecological integration for regreening in Kenya 'requires tools and processes that foster responsive external support for community empowerment, agency, and action' according to Fuchs et al. Transformation agendas need to be driven by local communities to ensure sustainable change.

Critical to scaling are farm advisors and extension networks. Jakku et al. highlight the role of advisors in longer term decision making for farmers, in a context of regional uncertainties in a changing climate. The authors show how advisors can be important trusted intermediaries for information and change practices, especially in contested spaces such as climate change, as they can make personal connections, and help understand regionally specific and long-term climate trends. Nettle et al. examine how smart farming technologies (SFTs) are changing the nature of work for advisors in the UK and Australia and present new insights on the bifurcation and specialization of roles, leading to increased importance of intermediaries, and those advisors engaging in "digiwork."

Digital transformation was investigated by Jakku et al. and Yeo and Keske. The latter used technology acceptance theory to show that "trust operates as a moderating factor to the desire for economic returns" in farmer decisions on technology investments. Increasing adoption of digital tools is therefore not just about theoretical financial benefits. However, without digital technologies presenting value to smaller scale farm businesses, these farms may be further marginalized.

Stone et al. examined the process of fostering agricultural transition and emphasize that farmers make decisions related to their specific context and should not be considered a homogenous group. Kuria et al., Manalo et al., and Stone et al. highlight that change is a nuanced process which can be incremental and/or transformative and there needs to be consideration of where the burden of change falls, as it is often placed upon the farmer. They call for rebalancing the burden across governance, food and farm systems. Nettle et al. also question where the responsibility lies for building advisory capacity to support transitions with smart farming technologies.

From this Research Topic we propose the following research agenda:

- What are benefits or costs and operational implications experienced by farmers when implementing transformative technologies and practices?
- What are the linkages between transformational practices and positive sustainability outcomes?
- How is transformation addressed in a context of deep uncertainty?
- How is responsible innovation enacted in farm-level transformations?
- What is the role of advisory networks that farmers require during transformative change?
- What are implications for advisors with respect to their work, roles, capacities and businesses?
- How can we improve our methodologies for assessing socioeconomic and sustainability impacts of farm system transformation and on-farm digitalization?

Author contributions

CE: Project administration, Conceptualization, Writing – original draft, Writing – review & editing, Investigation. JE: Investigation, Writing – review & editing, Project administration. JI: Investigation, Writing – review & editing, Conceptualization, Project administration. MA: Writing – review & editing, Project administration, Investigation. SF: Project administration, Writing – review & editing, Investigation. AR: Project administration, Investigation, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. At the time of writing, CE and JE were funded by New Zealand dairy farmers through DairyNZ Inc, Grant DNZ6384.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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frontiers | Frontiers in Sustainable Food Systems

TYPE Perspective
PUBLISHED 02 September 2024
DOI 10.3389/fsufs.2024.1456987

OPEN ACCESS

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RECEIVED 29 June 2024
ACCEPTED 19 August 2024
PUBLISHED 02 September 2024

CITATION
Stone TF, Nichols V and Thorsøe MH (2024) Exploring the position of farmers within the European green transition: transformation for whom?
Front. Sustain. Food Syst. 8:1456987.
doi: 10.3389/fsufs.2024.1456987

Exploring the position of farmers within the European green transition: transformation for whom?

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Food systems have been framed as a "wicked problem" due to the complex socio-ecological impacts they foster, ranging from contributing nearly a quarter of anthropogenic greenhouse gas emissions to a myriad of social impacts (e.g., health, food safety, and food security). In the European green transition for food systems, multiple actors are involved. However, farmers play a unique and critical role as agricultural land managers and navigators of social, political, and environmental factors. Using cover cropping and intercropping as examples, we illustrate the complexities arising when decision-making and governance at multiple levels lead to tradeoffs and unexpected consequences at the farm scale. Amid complexity, we propose a conceptual model to address the question: how is an agricultural green transition best fostered? We find that changes are incremental, transformative or both depending on the level of analysis. Additionally, incoherence in agronomic recommendations across academic disciplines and policy agendas creates challenges at the farm scale that trickle up and can thwart sustainable agricultural land use. Although transdisciplinarity and knowledge production with farmers through co-creation are essential for food system transformation and can be part of the solution, it is crucial to examine the nature of change processes and to consider how knowledge and innovation are adopted. By balancing top-down and bottom-up approaches and distributing burden from the farm scale to governance and food systems, a more transformative green transition for European food systems with coherence across multiple agroecological objectives could be achieved.

KEYWORDS

food system transformation, agricultural transition, sustainable farm systems, agricultural governance, transdisciplinary action research

1 Introduction

The unintended negative impacts of current food systems on people and the environment have been framed as a wicked problem (Rittel and Webber, 1973). Although much scientific literature and new policies have focused on transitioning toward sustainable agriculture as part of the European Green Deal (Peeters et al., 2020), how to foster a green transition continues to be contested and contextual (Boix-Fayos and de Vente, 2023). Some of the contestations arise from the broad range of approaches to sustainability transitions stemming from different disciplines and perspectives (Loorbach et al., 2017). Disciplinary differences can, to some extent, be addressed through transdisciplinary initiatives with frameworks for governance that include non-scientific actors to create horizontal co-innovation (Fernández González et al., 2021). However, in practice, agricultural governance includes varying degrees of diverse farmer engagement and empowerment in decision-making processes (Boix-Fayos and de Vente, 2023; Loorbach et al., 2017).

Farmers have been acknowledged as critical actors within agroecological transitions, they should not be seen as a homogeneous group but as a system of actors making decisions based on a diverse range of factors (Lacombe et al., 2018; Weituschat et al., 2022). This acknowledgment has inspired micro-AKIS and other co-innovation processes that include farmers, their networks, and other place-based factors as key components of transition processes (Lacombe et al., 2018; Sutherland and Labarthe, 2022). Despite the growing body of knowledge supporting participatory innovation models and co-concepts (e.g., co-production, co-design, co-learning), many conventional governance systems continue to pass the burden of transformative change mainly to farmers and their farm systems.

In this article, we first position ourselves within existing scholarship on the agricultural green transition. Second, we propose a conceptual model. Third, we use the conceptual model to explore two illustrative examples of a conventional scenario (cover cropping) and an exploratory scenario (intercropping) to highlight the implications for transition. Finally, we return to our initial research question and discuss how an agricultural green transition is best fostered.

2 Agricultural green transition

Transition is understood as both a concept and a process; reused knowledge is in a position of power, and ideally, actors should be able to leverage novel and established knowledge to make changes (Carlile, 2004). In this context, practical and political challenges should be recognized to explain innovation adoption (Carlile, 2004). The European agricultural green transition is similarly shaped by multiple actors and challenges. Power dynamics with governance systems as part of a socio-technical regime (e.g., policy, science, industry) shape the overarching goals, methods, and practical actions farmers are required to take (Geels, 2011). Conversely, participatory research and co-concepts have gained much political traction as effective means to enable transformative change (Hakkarainen et al., 2022). For example, designing agroecological farming systems with farmers by sharing project leadership provided a useful bridge between theory and practice (Lacombe et al., 2018). It enables farm system transformation by accounting for the diversity of farmers' situations and their local food systems (Lacombe et al., 2018). However, systemic and policy factors that create power dynamics, feedback loops and trade-offs influence farmer decision-making and have significant implications for the agricultural green transition (Gemtou et al., 2024).

When considering a green transition in Europe, although we acknowledge the plethora of actors, we find a simple conceptual model focused on burden and benefit distribution useful to understand why initiatives are not providing the transformative changes intended in the field of agriculture (Figure 1). The conceptual model for transitions in agriculture describes three scenarios (conventional, exploratory, and aspirational) across three broadly conceived organizational levels critical for transition: governance, food, and farm system for burdens, and society, food, and farm system for benefits.

The organizational levels would ideally distribute the burden and benefits of transition equally to enable a holistic transformation toward sustainability (aspirational scenarios). However, drawing on illustrative examples in Denmark, there are imbalances in burden and benefit distribution. In the conventional scenario (e.g., Denmark's cover cropping policies), burdens are concentrated at the farm system level, and benefits are concentrated at both societal and food system levels (e.g., environmental risk reduction and average percent of food cost to farmers compared to other actors in the supply chain). In a transition context, it is also important to understand the impacts of scenarios that are under exploration (proposed, not adopted). In the exploratory scenario burdens are concentrated at the governance level (e.g., intercropping), and benefits are concentrated at the societal level (e.g., farmers paying for carbon emissions). In many cases, farm system benefits are uncertain at best. To better contextualize this model, we will explore the present lack of equal burden distribution in conventional and exploratory scenarios and reiterate that burden balancing will require an intentional and collaborative effort.

3 Science meets policy meets farmer: two illustrative examples

Many agricultural practices are identified as potentially supporting an agricultural green transition (Wezel et al., 2014). Practices can be categorized into two main groups: those that entail increases in efficiency or substitutive practices and those that require some degree of redesign on a cropping systems or landscape level. For this exercise, we chose to select practices that require redesign, as they generally imply more complex interactions between sectors and systems. Among the redesign practices, cover cropping and changes in crop spatial distributions via intercropping have similarities we deemed advantageous in our context and are at different implementation stages from a policy perspective. Agronomically, the two practices have similarities in that implementing cover cropping or intercropping does not require specialized equipment or technology (although it can leverage them if available). While both practices may impact crop yields, the impacts are not of a magnitude that renders the practice either overly attractive or completely untenable to producers (Li et al., 2023; Marcillo and Miguez, 2017). Furthermore, the benefits of both practices are most significant and reliable at the societal level, with potential benefits at the farm level being possible, but to a lesser degree and with less certainty (Figure 1). This similarity in societal and farm-level benefit distribution, coupled with the distinct policy phases of cover cropping (advanced) and intercropping (nascent), rendered them ideal for exploring how burdens have been distributed in a conventional policy intervention, as well as how they are evolving in an exploratory phase of policy intervention.

In the European Union, Denmark implemented some of the earliest policies relating to cover crops stemming from the 1991 Nitrates Directive (Kathage et al., 2022) and has active research related to intercropping (e.g., Aare et al., 2021). We, therefore, chose to rely heavily on literature describing the current contexts of cover cropping and intercropping in Denmark. Denmark has historically exhibited some of the most comprehensive policy interventions related to agricultural production in the European Union (e.g., Andersen et al.,

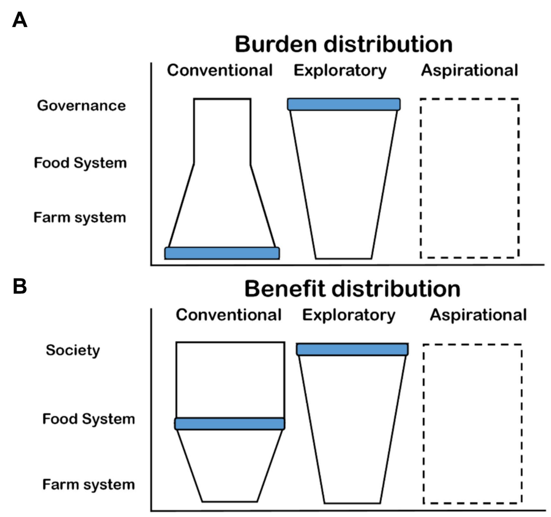

FIGURE 1
(A) Burden distribution and **(B)** benefit distribution conceptual models with three scenarios (conventional, exploratory, and aspirational) for an agricultural green transition with shapes representing burden or benefits across levels (narrow is less burden/benefit, wide is greater burden/benefit).

2017; Böcker and Finger, 2016), providing a richly documented and favorable context for comparison.

3.1 Conventional scenario: cover cropping

Annual cropping systems often result in periods where the soil is fallow, meaning there is no actively growing crop. In numerous temperate agricultural production systems, the fallow period exacerbates the risk of nutrients leaching from the soil, thereby polluting groundwater and surface water bodies (David et al., 2010; Withers et al., 2014). Cover crops (also known as catch crops) may be grown during these fallow periods to increase nutrient retention in the agroecosystem while concomitantly reducing nutrient pollution and are a common practice associated with green transition efforts (Boix-Fayos and de Vente, 2023; Figure 2). Recognizing the societal benefits that can be reaped from the use of cover crops in Denmark, a suite of policies has been incrementally enacted since 1985 that includes several regulations requiring actively growing plants in the autumn through the use of autumn-planted crops and cover crops (Dalgaard et al., 2014). When designed, the regulations had a singular focus on reducing nitrate leaching from agricultural land in Denmark, which influenced its implementation. These singular focus-driven policies have had transformational impacts on farm system planning and have unintentionally forced farmers to juggle contradicting best practices from various disciplines. For example, the policies have contributed to an increase in autumn-planted crops, which have been linked to the development of herbicide resistance in problematic weeds (Colbach and Dürr, 2003; Moss, 2017). The best management practices proposed to address this issue (e.g., delayed planting of winter crops) directly contradict practices encouraged by the cover crop policies (early planting of winter crops; Dalgaard et al., 2014). In Denmark, cover crops from the *Brassicaceae* family are effective at reducing nitrate leaching (Kumar et al., 2023). They are therefore favored by regulations, but can lead to disease carry-over into cash crops (e.g., *Brassica napus*). The policies focus on reducing excess nitrogen has also limited the use of leguminous cover crops and their attendant benefits (Allam et al., 2023; Snapp et al., 2005).

To maximize the probability of nitrate retention, requirements for timings of cover crop establishment have become increasingly calendar-based despite the increase in weather variability (Madsen et al., 2009). The timing requirements have also resulted in additional fieldwork during periods of the growing season that are both crucial to farmer's economic viability (e.g., crop harvest) and are subject to variable weather conditions. These small windows of high activity force farmers to make complicated decisions regarding trade-offs between following regulations when they may or may not be granted a weather exemption, incurring fines or other sanctions, harvesting their crops in a timely manner, and potential long-term soil compaction issues stemming from fieldwork on wet soils (Nawaz et al., 2013). Furthermore, the policies are updated and released on an annual basis, adding to the uncertainty farmers already face (e.g., weather, markets, labor availability) and making long-term crop rotation planning difficult. While the well-intended regulations have been part of a successful campaign in reducing nitrogen pollution on a national scale in Denmark (Kronvang et al., 2008), the narrow focus on nutrient management may have come at the expense of increased pesticide use (Guinet et al., 2023; Gunasinghe et al., 2020), loss of long-term soil fertility (Büchi et al., 2018), and reduced freedom for farmers to respond to situations in the most sustainable manner (Iversen et al., 2024). As a result, one could argue that the farm system has incurred the majority of the burden in this example.

3.2 Exploratory scenario: intercropping

Legume-cereal intercropping is a reemerging practice in the European green transition that includes growing two or more crops simultaneously in the same field. Although methods and species combinations vary widely, this practice, especially when implemented as a legume-cereal intercrop, has the potential to reduce environmental harm through the reduction of inputs (e.g., synthetic fertilizers) while maintaining stable yields and providing plant-based proteins for people and livestock (Glaze-Corcoran et al., 2020; Jensen et al., 2020; Maitra et al., 2021). Legume-cereal intercropping is not yet widely included in policy support schemes, but exploratory studies have looked at potential forms of policy support and necessary changes to the food system. These studies have suggested that changes needed to implement intercropping at the farm scale are minor compared to the transformations necessary at the food system and governance levels (Figure 2). For example, a wide range of actors participating in focus groups in Denmark and other European countries identified strategies to enable intercropping that primarily involved transformations in governance and food systems to be more flexible and diverse through system-oriented research and support schemes (Stone et al., 2024; Stone and Thorsøe, 2024, under review). A study in Denmark found similar results that for intercropping, farm-level issues (e.g., technical challenges, lack of knowledge) were less important than issues beyond the farm gate (Aare et al., 2021). Another Danish study highlights the host of actions needed by a variety of actors, in addition to farmers, to increase the use of species mixtures in Europe, including crop advisors, food system logistic managers, food ingredient producers, millers, machinery advisors and cooperative directors (Hauggaard-Nielsen et al., 2021). To enable widespread intercropped grains within food markets in Europe, a system for sorting or incorporating blended legume-cereal products or for providing the tested varieties and value chains necessary would require significant

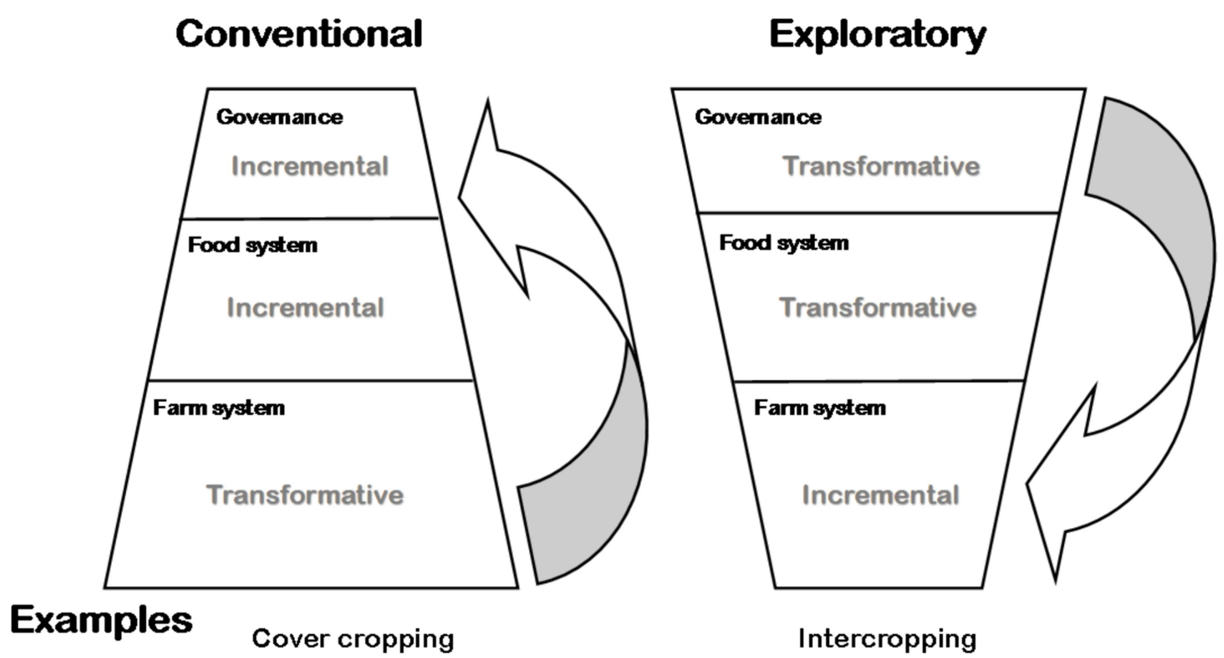

FIGURE 2
A conventional and exploratory burden scenario for a green transition in Europe with changes characterized as incremental or transformative at three levels (farm system, food system, and governance). With narrower sections representing less burden and the arrows representing re-distribution toward a more equal burden distribution.

buy-in and a series of transformations beyond the farm gate. Conversely, at the farm scale, intercropping can be incorporated into large and small, organic and conventional farming systems using similar equipment and methods already in use, and the required operations have less dramatic impacts on day-to-day operations and planning compared to cover cropping. Thus, in this example, the burden is concentrated at the governance and food system levels rather than at the farm level, as in the cover crop example.

4 Discussion: how is an agricultural green transition best fostered?

The illustrative examples exemplify that on-farm experimentation is not likely to produce a successful green transition unless integrated into a more comprehensive governance framework and value chain that aligns with and provides coherent support for new farming system models. Based on our model we propose that depending on the approach, transitions can be both incremental and transformational. Transition with increased burden distribution across levels, balancing influence from the top down and bottom up, could support more holistically transformative knowledge and innovation adoption in the context of the agricultural green transition in Europe.

The conventional and exploratory scenarios lack balance between top-down and bottom-up approaches and represent a lack of burden distribution across organization levels in European agriculture. Multi-level perspective transition models have addressed their potential bottom-up bias by developing transition pathways that offer different change scenarios balancing agency (e.g., farmer decision-making) and structure (e.g., governance; Geels, 2011). Geels et al. (2017) additionally emphasized the importance of alignment across niche, regime and landscape levels to support socio-technical transitions and provided a useful holistic framework for assessing niche momentum with innovation potential and the potential lock-ins based on regime tensions. In the context of low-carbon transitions, current regime stability and active resistance to changes by incumbent actors using politics and power were important to understanding systemic changes (Geels, 2014). Similar dynamics are essential to acknowledge and design for when considering an agricultural green transition.

Other models focus on farmer agency and highlight "good farmer" mindsets or inner dimensions that shape trajectories for sustainable farm system changes (Bakker et al., 2023; Guerra and Syed, 2024; Burton, 2004; Burton et al., 2020). Although our goal was to illustrate the position of farmers in transition, we found that governance and food system structures can limit agency at the farm system level, impacting some farmers more than others. Further, at the food system and governance levels, actors may have different interpretations of what constitutes the most critical challenge to address to support transition, as illustrated in the dairy sector (Thorsøe et al., 2020). In this transition context, inequalities may arise. For example, co-innovation processes centering farmers as co-producers of research in a living lab context without paying for their labor is emblematic of the imbalance in burden outlined in the conventional scenario. Given the European investment in living labs as an important model for the agricultural green transition, imbalances could grow despite attempts toward increased farmer participation, which might continue to include primarily privileged farmers.

The mission-oriented agricultural innovation systems approach highlights the direction-setting roles policymakers and the public sector have and emphasizes that it is essential to focus on who is excluded (Klerkx and Begemann, 2020). Greater inclusion in transition processes extended beyond the farmer to include a broader range of actors engaged in the food system, such as future farmers, eaters and activists could support more balanced transitions. A transformative change model for understanding local food systems also emphasizes the power political, bureaucratic, and public spheres of actors hold in a process of transformative incrementalism (Buchan et al., 2019). According to Buchan et al. (2019), "the path to transformative change is long, incremental, and laden with power relations and struggles." This intriguing model is also supported by Klerkx and Begemann (2020), who assert that transformation is made up of small wins instead of sudden radical changes.

From a systems perspective, different roles and actions will be required at each level to enable holistic transformations in agriculture. Research and innovation are challenging to fund in farmer-led initiatives requiring governance and the converse for implementation. These three levels (governance, food, and farm) also have their own interpretation of problems and how they should be addressed. Even when addressing the same problem, farmers may focus on the lack of legume markets, food system actors may focus on processor standards, and governance may focus on the resource shortage. This highlights the limits of top-down or bottom-up coordination across levels as each operates within different codes of meaning. Alrøe and Noe (2014) offer a polycular framework to address wicked problems, supporting various codes of meanings in interdisciplinary research, moving from first to second order observation (which shares multi-perspective orientation of transdisciplinarity; Fernández González et al., 2021). By adopting perspectivism as a scientific philosophy, science is seen as observer-dependent and thus supports many concurrent scientific truths related to complex problems, which has important implications for an agricultural green transition.

5 Conclusion

Amid tensions between bottom-down and top-up approaches and between agency and structure, we assert that a balance of these components is relevant in the context of an agricultural green transition. We found that a commitment to rebalancing burden across governance, food and farm systems is essential for positive transformative change toward food system sustainability in Europe. The implications for governance structures include the need to incorporate a systems perspective and a transdisciplinary approach to balance multiple priorities and practices in a way that can be effectively translated to a variety of conditions at the farm scale. Given the diverse and changing nature of environmental and social landscapes in which farm systems operate, coherent yet place-based policies could deliver an enabling policy environment for the agricultural green transition. In this context, utilizing social theory and evidence-based practices within research and policy development processes is critical to overcoming challenges. Future transdisciplinary action research to analyze and recommend food and farm system scale policy schemes based on their system transition potential would be useful, but only if there is buy-in and willingness to adopt changes across levels of governance. Fostering environments where a diverse group of farmers, researchers and policymakers can co-create agendas for a sustainable future agriculture means acknowledging power dynamics within the present food system regime. Many stakeholders may also need to adopt new methodologies, skillsets, terminologies and even philosophies of science. Fine-tuning approaches to address sustainable transition challenges by applying them across governance, food and farm systems through iteration and compromise could support sustainable farming and enable the agricultural green transition desired by the European Green Deal.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

TS: Conceptualization, Visualization, Writing – original draft, Writing – review & editing. VN: Conceptualization, Writing – original draft, Writing – review & editing. MT: Conceptualization, Writing – review & editing.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Acknowledgments

Grammarly (v.1.2.94.1468) was utilized in the final proof read process to correct for grammatical errors.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 18 September 2024
DOI 10.3389/fsufs.2024.1456620

OPEN ACCESS

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RECEIVED 28 June 2024
ACCEPTED 04 September 2024
PUBLISHED 18 September 2024

CITATION
Kuria AW, Bolo P, Adoyo B, Korir H, Sakha M, Gumo P, Mbelwa M, Orero L, Ntinyari W, Syano N, Kagai E and Fuchs LE (2024) Understanding farmer options, context and preferences leads to the co-design of locally relevant agroecological practices for soil, water and integrated pest management: a case from Kiambu and Makueni agroecology living landscapes, Kenya. *Front. Sustain. Food Syst.* 8:1456620. doi: 10.3389/fsufs.2024.1456620

Understanding farmer options, context and preferences leads to the co-design of locally relevant agroecological practices for soil, water and integrated pest management: a case from Kiambu and Makueni agroecology living landscapes, Kenya

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Agroecology, as a holistic approach to sustainable food systems, is gaining momentum globally as a key approach to addressing current challenges in agricultural and food production. In sub-Saharan Africa, despite numerous efforts to address declining soil productivity, water scarcity, and increasing pest pressure through agroecological soil, water, and integrated pest management (IPM) practices, the adoption of such practices remains low. As part of the CGIAR Agroecology Initiative, we conducted a collaborative rapid innovation assessment of existing soil, water, and pest management practices in two Agroecological Living Landscapes (ALLs) in Makueni and Kiambu counties, Kenya. The assessment also included an evaluation of the performance of these practices and identified farmer preferences. Using a multi-stage approach, we applied stratified random sampling to identify 80 farmers for farm assessments and in-depth interviews. A total of 31 practices were identified, of which 26 were further evaluated. The evaluation revealed a heterogeneous set of socio-economic and biophysical contextual factors influencing practice performance. Respondents identified 19 strengths, and 13 challenges associated with the practices, highlighting opportunities for innovation to improve or adapt performance. Farmers also expressed preferences for future adoption of 31 practices, 77% of which were listed in one of the three focus areas, namely soil management, water management, or IPM. The other 33% were associated with multiple functions and were listed under two or three of the focus areas. The results of the collaborative assessment informed a broader co-design cycle that included participatory prioritization and selection of innovative practices, experimental design, and monitoring protocols. This collaborative and systematic approach was taken because innovative practices often fail to be adopted due to a lack of co-design and inclusion of local perspectives in innovation design, and a disconnect between science and practice. Our study highlights the importance of integrating stakeholder input and transdisciplinary technical expertise in the co-design and implementation of agroecological innovations. It also emphasizes the importance of using a structured methodology to understand farmers' options, context, and preferences while co-designing locally relevant agroecological practices, which promotes holistic and inclusive adoption, successful implementation and long-term sustainability of agroecological practices.

KEYWORDS

agroecology, soil management, water management, integrated pest management, options by context, farmer preference, participation, co-design

1 Introduction

The concept of agroecology is gaining traction globally as a key approach to comprehensively addressing the current challenges facing food production. Agroecology involves a synthesis of both agronomic and ecological principles that integrate social, environmental and economic dimensions. It emphasizes the promotion of biodiversity and associated ecosystem services to sustain agricultural production and promote resilient, environmentally sound and sustainable food systems (Wezel et al., 2009; Zanasi et al., 2020). It does so by harnessing biological interactions and seeking to optimize the relationships between plants, animals, soils and the surrounding ecosystems (Jones et al., 2022; Nicholls and Altieri, 2018). Agroecological practices include a range of methods and techniques through which the 13 agroecological principles are applied (HLPE, 2019; Wezel et al., 2020).

The agroecology principles are nested under three operational principles. The first category nests two principles, recycling and input reduction, which improve resource efficiency by optimizing resource use to increase economic returns and reduce negative environmental impacts. The second category nests five agroecological principles that strengthen resilience by improving the adaptive capacity, risk management, and response to changing conditions. This includes principles three through seven, namely soil health, animal health, biodiversity, synergy and economic diversification. The third operational principle consists of six principles that secure social equity by promoting fairness and accountability in addressing a broad spectrum of social and ethical concerns within societies. These principles include co-creation of knowledge, social values and diets, fairness, connectivity, land and natural resource governance and participation (HLPE, 2019). Consistent with the emphasis on principles to define what agroecology entails, there is no single set of farming practices that can be defined as agroecological in nature. Rather, agroecology is about the contextual operationalization of these 13 principles. However, it does point to relevant subsystems that should be considered, including soil, biodiversity, and others.

In this context, the importance of simultaneously adopting agroecological practices related to soil management, water management, and integrated pest management (IPM) has been emphasized. All three of these interrelated components are of paramount importance in promoting sustainable food systems (McIntyre et al., 2001). For example, poor and infertile soils with little or no organic matter have been found to not only retain little or no water and moisture that is necessary for plant growth but are also prone to erosion due to weak soil structure (Regelink et al., 2015). Further evidence shows that unhealthy and infertile soils lack diversity, biomass and abundance of beneficial soil macrofauna (Ayuke et al., 2011) and microfauna (Bolo et al., 2021, 2024). Schroth et al. (2000) further state that systems with low plant diversity are less resilient and are more susceptible to pests and diseases, leading to higher pesticide use. Deepika and MubarakAli (2020) note that there has been an increase in the use of synthetic fertilizers to address the high nutrient deficiencies in the soil. This reliance on synthetic fertilizers and pesticides has been shown to result in the loss of beneficial soil macrofauna and contamination of water bodies and food crops (Solgi et al., 2018). Therefore, a holistic approach that integrates soil management, water management, and IPM is key to building resilient and sustainable agricultural systems.

In sub-Saharan Africa, there is a clear need to focus on and invest in integrated soil, water and pest management. For example, soil productivity is declining due to various factors such as land degradation, declining fertility, and poor health due to inefficient soil management practices (Raimi et al., 2017), including nutrient mining, removal of crop residues from the farm, and overcultivation without adding more organic matter to the soil (Blanco-Canqui and Lal, 2009; Majumdar et al., 2016). Agroecological soil management practices are therefore essential to maintain soil fertility, biodiversity, structure, and nutrient levels among other important requirements for optimal crop growth (Barrios et al., 2006; Chikowo et al., 2014). Such practices take advantage of ecological system interactions, including the use of ecosystem-friendly farm inputs, and prioritize nurturing healthy soils as the foundation for productive and resilient farming systems (Gliessman, 2018). They discourage the use of chemical inputs such as inorganic fertilizers and instead advocate for holistic, regenerative and sustainable practices that maintain or improve soil health over time (Hathaway, 2016; Wezel and Soldat, 2009). These include practices such as cover cropping, crop rotation, mulching, organic manure and soil amendments to improve soil fertility and structure (Alyokhin et al., 2020; Bolo et al., 2023).

Water management is equally critical in sub-Saharan African farming systems, where water scarcity is a persistent challenge that threatens livelihoods (Gaspard and Authority, 2013). Major causes of water insecurity include deforestation, climate-related drought and poor soil water management practices such as lack of rainwater harvesting and soil water conservation (Demeke, 2003; Mango et al., 2018; Shiferaw et al., 2014). Water scarcity and soil water deficit are particularly prevalent in arid and semi-arid areas that receive low rainfall amounts (Ong et al., 2007). Agroecological water management practices that prioritize the efficient and responsible use of water resources include rainwater harvesting, mulching, conservation agriculture, and the use of cover crops to enhance water retention in the soil and reduce water runoff (Altieri et al., 2015; Hermans et al., 2021). In addition, promoting diversity, including agroforestry, and integrating soil organic matter contribute to soil aggregate stability, increased water infiltration and retention, and reduced soil erosion (Bargués-Tobella et al., 2024; Liu et al., 2019; Winowiecki et al., 2021).

As a result of global warming, the sub-Saharan African region is experiencing increased temperatures and a concomitant increase in pest incidences, which contribute significantly to reduced agricultural productivity. Other factors contributing to increased pest incidences include declining biodiversity due to the promotion of monocropping systems, continuous cultivation without fallow periods, and the use of low-quality planting materials (Abate et al., 2000; Ratnadass et al., 2012). While conventional pest management promotes overreliance on chemical pesticides that kill rather than manage pests, and lead to the contamination and pollution of ecosystems (Barzman et al., 2015), IPM is an agroecological approach that provides a comprehensive and sustainable approach to pest management by integrating different strategies while maintaining ecosystem balance and minimizing health, environmental and economic risks. IPM typically combines biological, natural, cultural, mechanical, physical and host plant resistance technologies (Morales, 2004). It includes practices such as the use of natural predators, plant-based biopesticides, crop species diversification, and the use of companion planting to disrupt pest life cycles and pest-tolerant crop varieties (Deguine et al., 2021).

Despite practices falling under all three focus areas being implemented in sub-Saharan Africa (Debray et al., 2019; Nyantakyi-Frimpong et al., 2017), the region continues to experience low adoption of agricultural innovations, where adoption refers to the integration of an innovation into farmers' normal farming activities over an extended period of time, preceded by a period of trial and adaptation to the local context (Loevinsohn and Sumberg, 2012; Ruzzante et al., 2021); and low crop productivity and food insecurity remain prevalent. One of the main reasons for this is the failure of external agents promoting such practices to elicit the participation of relevant stakeholders, including target adopters, in the co-design of context-specific agroecological practices (Chave et al., 2019; Magrini et al., 2019).

Co-design refers to the active and creative collaboration among stakeholders in the design and implementation of solutions to a pre-specified problem (Sanders and Stappers, 2008; Goodyear-Smith et al., 2015; Steen, 2013). Unlike user-centered approaches that incorporate the views and needs of end users of agricultural technologies (Ortiz-Crespo et al., 2021; Rose et al., 2018), or participatory action research where stakeholders participate in decision making throughout the design and implementation process (Baum et al., 2006; Cornish et al., 2023), co-design typically builds on the tradition of participatory design. Here, the roles of different stakeholders change throughout the co-design process, and the people who will ultimately benefit from the design process sometimes take on the role of "experts of their experience," leading to the generation and sharing of knowledge and ideas (Sanders and Stappers, 2008). Consequently, co-design is a specific example of knowledge co-creation, where new knowledge is generated as stakeholders develop and experiment with new ideas resulting in new concepts and solutions that are context-specific and locally relevant (Mauser et al., 2013). Co-design processes thus promote transdisciplinary science, where stakeholders from different disciplines come together to co-create knowledge to solve complex social, political, environmental, educational and technological problems through the generation of new knowledge (Falconnier et al., 2017). Co-creation of knowledge, which refers to the collaborative generation of knowledge by different stakeholders, is described as more participatory, inclusive, holistic, and equitable for diverse actors, and as having better outcomes in adoption of and commitment to agroecological practices (Utter et al., 2021).

Our team adopted a rather broad definition of co-design as representing the highest level of participants' engagement in design, decision-making, and implementation. We consider a continuum of consultation, involvement, participation, and co-production/co-design. The distinction between co-design and participatory design is often blurred in practice, and which term is most appropriate depends on the specific context. The term co-design itself has also evolved, resulting in different interpretations and applications, which contributes to terminological ambiguity. While the term co-design typically implies that a collaborative and iterative process is implemented, some focus more on creativity, exploration, and the discovery of new possibilities that emphasizes understanding user needs and fostering innovative solutions (Sanders and Stappers, 2008). Others use the term co-design in contexts that are more solution-oriented, focusing on the co-creation of practical, context-specific interventions through structured and goal-oriented processes aimed at implementation rather than exploration (Neef and Neubert, 2011). The structure and subsequent co-design process that we adopted are consistent with this latter interpretation: a participatory, solution-oriented co-design methodology aimed at co-developing actionable strategies with stakeholders. The rapid innovation assessment itself, which aimed to explore farmers' practices and preferences, while conducted through a structured research-driven approach, focused on exploration and discovery as critical input for the more solution-oriented co-design workshops.

Our approach retains essential co-design elements such as collaboration, problem-focused, solution-oriented, inclusive, reflexive, iterative and stakeholder engagement (Rosendahl et al., 2015). In a recent meta-analysis of 88 publications, Busse et al. (2023) categorized intervention-oriented co-design approaches into four subtypes namely the "researcher-led and model-based" and "social science-driven intervention" studies that use a rigorous, predefined study design in which scientists are the dominant actors. The third subtype includes studies that develop "design-led and practice-oriented interventions" rather focus on practical outcomes than on scientific knowledge production. The fourth subtype, to which our current study aligns, is "transformative transdisciplinary interventions and living labs," which have the strongest ties to transdisciplinary research philosophy, theory, methodology, and practice.

The concept and practice of co-design have been widely applied in different agricultural contexts. For example, Klerkx et al. (2012) advocate for a transdisciplinary and systems approach to address the complex socio-economic and natural context of farming systems by promoting participatory and co-design processes in the design and implementation of interventions. This is further supported by Berthet et al. (2018) who note that the complexity of agricultural innovations requires a systems thinking approach and facilitation process. However, despite their widespread application in agricultural systems, the optimal outcomes of agroecological transitions are often not fully realized. Therefore, for co-design processes to lead to responsible innovations in agricultural systems, human-centered design (HCD) approaches are required that promote four key dimensions namely inclusion, responsiveness, reflexivity and anticipation (McCampbell et al., 2022). This also requires ensuring that the co-design process is ethical and genuine by involving local communities in decision-making and shaping their current and future livelihoods (Sendra, 2024).

The adoption of generalized and top-down approaches and the lack of co-design of innovative agricultural practices can lead to a disconnect between scientific knowledge and the practical local realities of farming systems (Eilola et al., 2014). This is echoed by Reichelt and Nettle (2023) who observe that responsible innovation principles, which value the voices of diverse stakeholders, have not been widely applied to the adoption of innovative agricultural practices. The lack of local participation is often associated with an underestimation of the local heterogeneous and dynamic context of smallholder farming systems (Kuria et al., 2019; Vanlauwe et al., 2014) and an inadequate understanding of the context of their farming systems such as the nature, appropriateness and effectiveness of the agricultural practices and options they are already implementing (HLPE, 2019). It also leads to a limited understanding of the context-specific constraints and barriers that may hinder the success of agroecological practices (Sinclair and Coe, 2019). This can result in the promotion of agroecological options that are not locally appropriate, relevant, or adapted to the context of smallholder farming systems (Farrow et al., 2016), rather than using demand-driven and responsive approaches that are more likely to succeed in promoting actual behavior change (Fuchs et al., 2019a; Fuchs et al., 2022). Effective adoption of agroecology therefore requires a systems approach (Sinclair, 2017) and the integration of transdisciplinary perspectives and involves collaboration and co-creation of knowledge between farmers, researchers, and other stakeholders to develop context-specific agroecological practices (Calvet-Mir et al., 2018; Fernández González et al., 2021; Wezel et al., 2020). This also comes from documenting what people already know about agroecological practices and identifying knowledge gaps, which are then addressed.

In addition, the lack of local participation also results in a lack of consideration of farmers' perspectives, preferences, and needs. Farmers' preferences in agriculture are diverse and influenced by several factors, ranging from personal values, geographic and climatic conditions to Market trends and personal experiences (Duguma and Hager, 2011; Martin-Collado et al., 2015). These preferences include choices related to the crops they grow, whether they have livestock, land size, family size, their knowledge of agricultural techniques, their assessment of risk, and their future aspirations for their livelihoods (Knapp et al., 2021; Villacis et al., 2023). Fuchs et al. (2023a) posit that "communities will uptake and sustainably engage in such activities, if the practices promoted by the external actor are aligned with who they are, their livelihood activities, and what they like; and hence based on, and responsive to, local identities, interests, and preferences (IIP)." They define local IIP as "the quintessence of people's complex life aspirations, influenced by their socio-cultural background, their rational calculations, and their personal taste" (p. 2). Therefore, in this study, we hypothesized that co-designing contextually relevant agroecological practices would lead to knowledge co-creation, which in turn would contribute to agroecological transitions by optimizing existing practices and innovating and redesigning smallholder systems to increase production efficiency and ecological resilience (Duru et al., 2015; Stratton et al., 2021).

Our study aimed to document all the existing agroecological farming practices in two so-called Agroecological Living Landscapes (ALLs) in Makueni and Kiambu counties, Kenya. Specifically, we investigated practices related to the three focus areas discussed above, namely soil management, water management and IPM (Kuria et al., 2023). After identifying existing options, the second objective was to understand the context of each practice's performance, including by jointly identifying the strengths and weaknesses (barriers, gaps, and costs) of the agricultural practices that farmers were currently implementing, and third, to identify farmers' preferences for innovative agroecological soil, water and IPM practices. After presenting the methods used in the rapid innovation assessment on which this study is based, and sharing and discussing the results in terms of options, context, and preferences, we contextualize the rapid innovation assessment in terms of how it informed the broader co-design cycle that led to a participatory prioritization of agroecological practices that were subsequently piloted and put under trial by ALL farmers in Kiambu and Makueni counties (Fuchs et al., 2023b).

2 Materials and methods

2.1 Study area

The study was implemented in two agroecological living landscapes (ALLs), which are geographically bounded landscapes where smallholder farmers, agroecology practitioners, researchers, and other development actors have been engaged to identify, test and promote agroecological innovations across sectors and scales in Kenya. The two ALLs emerged from a comprehensive selection and engagement process conducted by the CGIAR Initiative on Agroecology (or Agroecology Initiative) beginning in September 2022 (Fuchs et al., 2023b). The targeted and purposive selection process included the identification of so-called ALL host centers, which provide a physical space where food system actors can meet and interact in the spirit of co-learning and knowledge co-creation. The Agroecology Initiative is a collaborative partnership of nine CGIAR entities, as well as CIFOR-ICRAF, the French research institute CIRAD, and the Agroecology Transformative Partnership Platform (TPP). Implemented in eight countries, the main objective of the Agroecology Initiative is to promote the application of contextually appropriate agroecological principles by farmers and communities in different contexts, with support from other food system actors.

Specifically, the study focused on the two ALLs located in Makueni and Kiambu counties (Figure 1). Makueni County covers an area of 8,214 km^2 between latitudes 1°35′ and 2°59′ south and longitudes 37°10′ and 38°30′ east, and has a population of 1,098,584, while Kiambu County covers an area of 2,543.5 km^2 between latitudes 00°25′ and 10°20′ south and longitudes 36°31′ and 37°15′ east. Kiambu County has a population of 2,417,735, making it the second most populous county in Kenya after Nairobi, Kenya's capital city. The

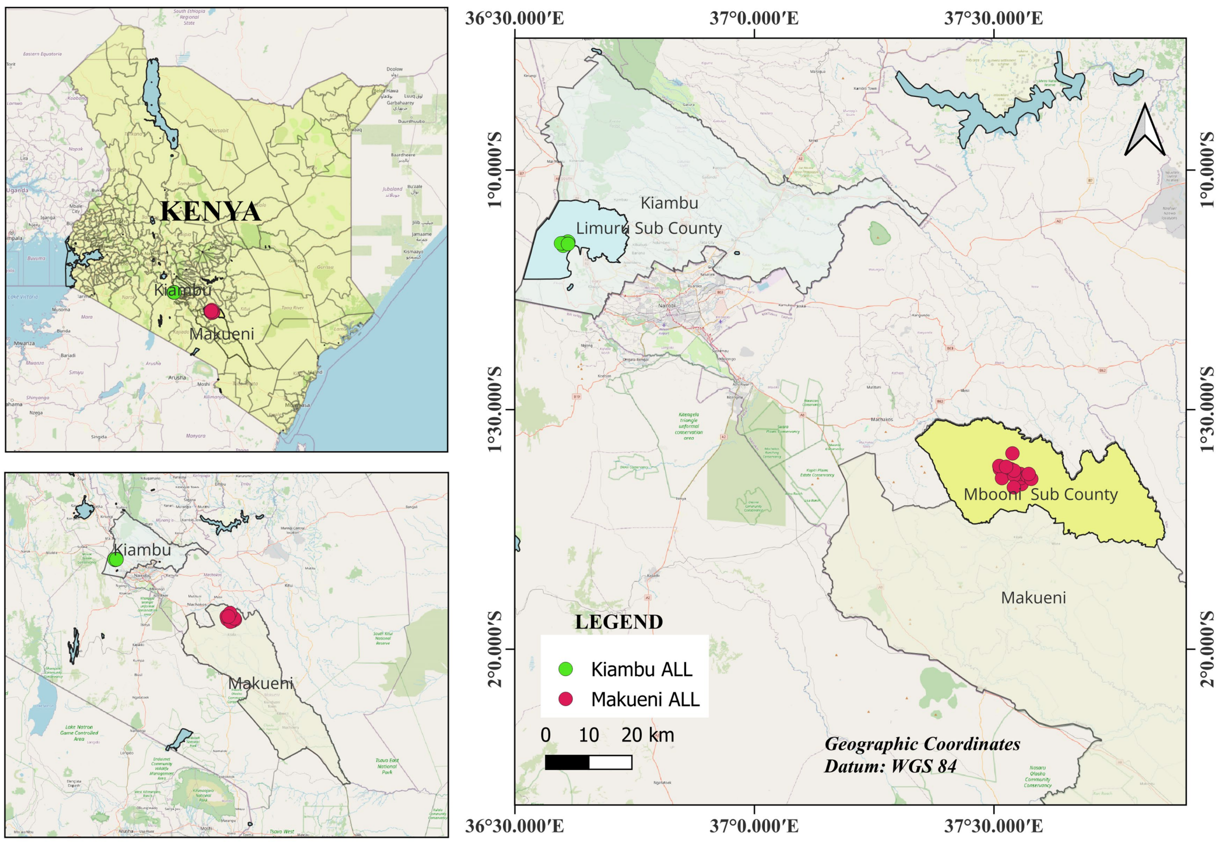

FIGURE 1
Map of the study and intervention areas in Kiambu and Makueni ALL.

two counties have different topography, climate, and soil conditions. Makueni County has a low-lying terrain with hilly areas receiving 800–1,200 mm of rainfall annually, while lower regions such as Kibwezi East receive 250–400 mm. Mean temperatures range from 20.2 to 35.8°C, with cooler temperatures in the hilly areas, and average annual rainfall of 500–750 mm of (Nyawira et al., 2023). The Drylands Natural Resources Center (DNRC) is the Makueni ALL host center. DNRC is a registered non-governmental organization (NGO) whose primary goal is to promote sustainable development of the resources of the drylands of Kenya through permaculture and agroecology. In Kiambu County, there are four topographic zones with different altitudes and agricultural activities. The upper highlands act as a water catchment area, while the lower highlands are suitable for tea and dairy farming. The midland zone faces challenges of soil erosion (*ibid*). Despite Kiambu's generally humid climate, with annual rainfall ranging from 600 to 1,600 mm, semi-arid areas such as Ndeiya receive about 500 mm of rainfall annually, with April being the wettest month and July the driest. The Community Sustainable Agriculture and Healthy Environment Program (CSHEP), a registered community-based organization (CBO) in Ndeiya that focuses on training smallholder farmers in agroecological and organic practices, is the host center for the Kiambu ALL. The Agroecology Initiative's agriculture-related activities in the early stages of implementation focused primarily on the areas surrounding the two ALL host centers, while other activities spread more widely across the ALLs.

2.2 Sampling strategy

A total of 80 farmers equally distributed between the two ALLs were interviewed in this collaborative rapid innovation assessment study. A stratified random sampling approach was used to ensure representation of the diverse and heterogeneous study areas. This approach aimed to create a sample that accurately reflects the biophysical and socioeconomic context and characteristics of the entire population. In doing so, the study enhances generalizability, promotes external validity, and mitigates research bias.

Stratified random sampling was conducted in collaboration with the ALL-host centers using a multi-stage approach based on five key factors: program participation (program and non-program farmers), geography (villages), gender, age, and land size. For example, in the Kiambu ALL, the study interviewed 27 farmers previously trained by Community Sustainable Agriculture and Healthy Environmental Program (CSHEP) host centers and 13 non-CSHEP farmers. In the Makueni ALL, 30 farmers affiliated with the Drylands Natural Resources Centre (DNRC) and 10 non-DNRC farmers were included in the sample. In the Kiambu ALL, farmers were selected from nine villages in Ndeiya sub-county and ward, including Gitutha, Makutano, Nderu, Boma, Gatarakwa, Kameria, Mirithu, Michofo, and Kiawanda (Figure 1). In the Makueni ALL, farmers were sampled from Mbooni East sub-county, with villages selected from two wards: Kiteta Kisau and Waiya Usalala. Overall, this rigorous sampling approach ensures that the study captures a representative sample from diverse backgrounds and contexts within the ALL regions.

2.3 Data collection and analysis

Prior to the commencing the study, ethical approval was sought to ensure that the rights, dignity, and welfare of participants are protected. We first submitted details of the planned research to the ICRAF Ethics Committee, outlining the study's aims, methods, and potential impact of the study on participants, and obtained approval (Jordan and Gray, 2014). In addition, prior to interviewing the farmers, we obtained informed consent by providing each participant with comprehensive information about the study, including the study's objectives, proceeding, data anonymization, voluntary participation, and the ability to withdraw at any time without penalty (Cooper et al., 2016; Singer, 2004). This ethical framework ensured transparency, demonstrated respect for participants' autonomy, and maintained the integrity of the research process.

Data were collected in February 2023 through a survey consisting of semi-structured questionnaires administered by researchers who visited and interviewed the farmers at their homesteads and farms. The process involved the researchers asking the questions verbally and then recording the farmers' responses on paper questionnaires. The survey tool was modeled on and informed by previous engagement activities, particularly the contours of the "mobilizing narratives" identified to operationalize the "communities of place" that would be engaged in the respective ALLs in November 2022, as well as subsequent engagements that generated community visions for desired future changes that could accelerate agroecological transitions in the ALLs (Fuchs et al., 2023a). The results of these transdisciplinary exercises helped to identify the key challenges that stakeholders were collectively interested in addressing in agroecological transitions and allowed categorizing them into the three main focus areas (soil, water, and integrated pest management) in which solutions were subsequently co-created. These focus areas served as a roadmap for developing tools for further research and became the conceptual vehicle for future co-design engagements.

The survey covered general farm and farmer characteristics, existing innovative agroecological practices, the context of their implementation and performance, availability of practice-specific materials, sources of knowledge related to their implementation, farmers' understanding of the underlying scientific mechanisms, strengths and challenges, costs and labor requirements, associated crops, etc. Both open- and closed-ended questions were used. Questions related to socio-demographic and farming system characteristics were primarily closed-ended, while those assessing practices combined closed-ended and open-ended questions. The inclusion of open-ended questions, which refers to questions that do not have a set of response options (Züll, 2016), allowed farmers to provide detailed contextual information based on their personal experiences. To ensure that specific agroecological practices were correctly identified and mapped to their respective focus areas, keeping in mind that many practices serve multiple purposes and may be mapped to two or more focus areas depending on farmer's practice, the team developed an initial complementary classification of all soil, water, and integrated pest management practices—including agroecological and non-agroecological (Kuria et al., 2023). A team of researchers from CIFOR-ICRAF, the Alliance of Bioversity International and the International Center for Tropical Agriculture (CIAT), the International Institute of Tropical Agriculture (IITA), and the ALL-host centers provided training and pre-testing, and administered the questionnaires.

The collected data were cleaned by removing outliers, correcting spelling errors, removing duplicate entries, and checking for errors and inconsistencies (Osborne, 2010). Next, qualitative data from open-ended questions were coded, either by assigning numerical codes or by reclassifying responses from open-ended questions into broader categories to facilitate statistical analysis (He and Schonlau, 2020). The data were then subjected to descriptive analysis and visualized in a variety of ways, for example, the socio-economic characterization of farmers and the results of the co-design trial prioritization were presented in tables. R software (R Core Team, 2020) was used to generate heat maps that were used to visualize cross-tabulation results, namely all agroecological practices found on farms, strengths, benefits and challenges associated with inventoried agroecological practices, while ggplots were used to visualize practices inventoried by farmers and costs associated with different practices. ATLAS.ti software (ATLAS.ti Scientific Software Development GmbH, 2023) was used to generate Sankey diagrams of farmer's future preferred practices and to illustrate the multiple functions preferred in the three focus areas of soil management, water management, and IPM.

2.4 The co-design workshop process methodology

As mentioned above, the rapid innovation assessment was conducted in the context of a broader co-design cycle (Figure 2), the main objective of which was to test and put co-created innovative agroecological practices under trial in both ALLs (Fuchs et al., 2023b). The first actual co-design design workshop was highly methodical and followed a clear sequence. We held three-day integrated workshops in each of the ALLs between July and August 2023, bringing together farmers, ALL host centers, the Agroecology Initiative project team, and additional research, technical and extension stakeholders together to discuss the most appropriate and desired options to be tested through trials at the ALL centers and in farmers' fields (Watts-Englert and Yang, 2021). Willing and agroecology-motivated participants were purposively selected to ensure broad representation, with 15 individual farmer groups selected and two members (a man and a woman) per group invited to the workshops. At least 50% of the farmers who participated in the co-design workshops had also been interviewed during the rapid assessment.

The co-design workshops consisted of seven steps. In step 1, the results of the rapid assessment, which included the participating farmers' own views, were presented to the stakeholders. To visually support the data sharing, we prepared posters for each of the top three to five practices per focus area that provided a simple overview of the key findings from the innovation assessment. This included a broad set of existing soil, water and IPM options encountered and the context including benefits, challenges and preferred innovative practices identified. In Step 2, participants added other innovative practices that had not been identified or highlighted by the Agroecology Initiative team. Step 3 was to collectively narrow down the list of preferred innovations to a few agroecological innovations to be tested in

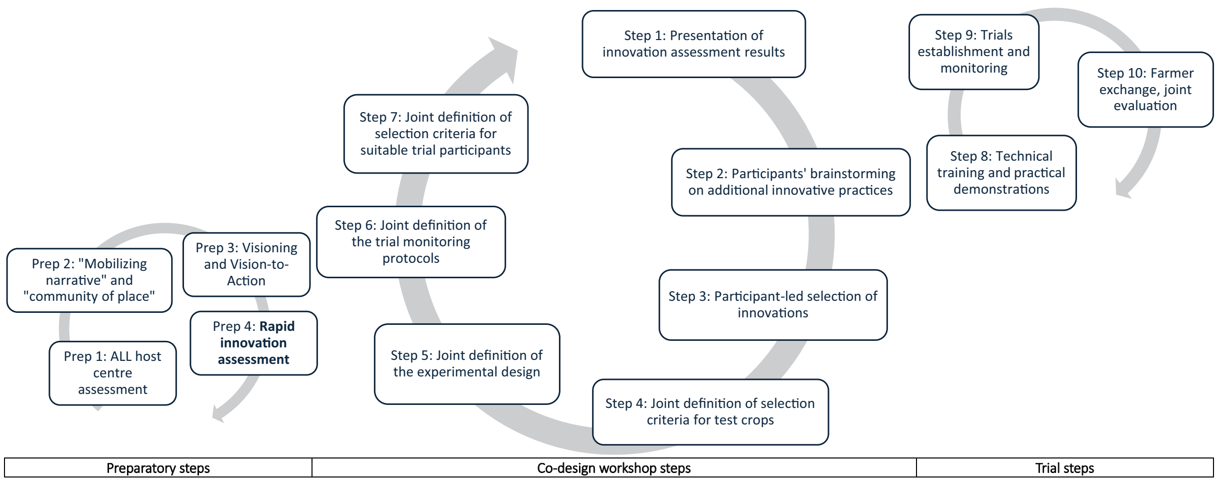

FIGURE 2
Stepwise proceeding followed in the onfarm innovation codesign.

monitored trials. After selecting the respective practices, Step 4 involved deliberations among participants on relevant selection criteria and the selection of the respective host test crops. Step 5 involved defining a strategy for setting up the trials for the selected agroecological innovations. Step 6 involved the development of appropriate protocols for the evaluation of the selected agroecological innovations, in which the farmers discussed desirable, measurable and observable criteria. Step 7 involved the collective identification of criteria for identifying the trial participants and a preselection of the participants. Once the co-design workshops were completed, two additional steps included Step 8, which involved technical training including practical demonstration of trial establishment in the ALL centers. After that the trials were established with the onset of the rains in a last step.

3 Results

3.1 Socio-economic characterization

The average household land size was 1.73 ha in the Makueni ALL and 0.84 ha in the Kiambu ALL respectively, while the average age of the interviewed farmers was 56 years in both ALLs (Table 1). More than 70% of the farmers interviewed in both ALLs were female, while more than 72% of the households sampled were male headed. Almost all (96%) respondents indicated farming as their main source of livelihood. Food self-sufficiency was recorded at 8.2 ± 4.0 months in Kiambu and 6.6 ± 3.7 months in Makueni. The top four crops grown in Kiambu were maize, beans, vegetables, and Irish potatoes; while maize, beans, cowpeas, and pigeon peas were the top four crops grown in Makueni. Most respondents reported practicing natural or ecological farming (85% in Kiambu, 72% in Makueni), and agroforestry (85% in Kiambu, and 98% in Makueni). Soil quality was described as "medium" by most farmers (78% in Kiambu, 51% in Makueni), with a considerably higher percentage in Makueni (28%) describing it as "low." In both the Makueni ALL and the Kiambu ALL, all farmers reported experiencing climate and yield changes in their main crops over the past 5–10 years. The two most common climate-related changes identified by farmers were drought due to low rainfall (52 respondents; 65%) and poor yield (29 respondents; 36%).

TABLE 1 Socio-economic characteristics of farmers in Kiambu and Makueni ALLs.

Characteristics	Kiambu ALL $n = 40$	Makueni ALL $n = 40$	Overall $n = 80$
Farm size (ha)	0.84 ± 0.76	1.73 ± 1.44	1.29 ± 1.23
Age	56 ± 15	56 ± 13	56 ± 14
Gender			
Females	29 (72%)	31 (78%)	60 (75%)
Males	11 (28%)	9 (22%)	20 (25%)
Family type			
Female-headed household	12 (30%)	10 (25%)	22 (28%)
Male-headed household	28 (70%)	30 (75%)	58 (72%)
Family size	4.77 ± 1.83	5.78 ± 1.85	5.28 ± 1.89
Level of education			
None	1 (2.6%)	1 (2.5%)	2 (2.6%)
Primary	15 (39%)	22 (55%)	37 (47%)
Secondary	20 (53%)	14 (35%)	34 (44%)
Tertiary	2 (5.3%)	3 (7.5%)	5 (6.4%)

Data are presented as number (percentage); mean ± standard deviation.

3.2 Existing soil, water and integrated pest management practices identified by farmers

A total of 31 agroecological practices were identified on respondents' fields in both ALLs, with 29 and 18 practices being mentioned in Kiambu and Makueni, respectively. There were 18 common practices, while 13 were unique to the sites. While many practices do serve multiple purposes, no practice was mentioned in all three focus areas during the options inventory. Practices that farmers reported implementing for both soil and water management were agroforestry, mulching, raised beds, sunken beds, terraces and zai pits. Practices that farmers implemented for both soil management and IPM were crop rotation and intercropping.

A total of 16 soil management practices were classified by farmers as being used for soil management, with all 16 reported by the farmers in the Kiambu ALL and 9 in the Makueni ALL (Figure 3). Farmyard manure (61%) and compost manure (53%) were the most reported soil management practices mentioned in both ALLs. Crop rotation (33%) and intercropping (30%) were more frequently mentioned in Kiambu while agroforestry (40%) and terraces (33%) were more commonly mentioned as serving soil management functions in Makueni. Similarly, 16 practices were reported to have water management functions. Thirteen of these were mentioned in Kiambu and 10 in Makueni. In Kiambu, the main water management practices reported by farmers were mulching (35%), multistorey kitchen gardens (30%), and water recycling (30%). In Makueni, water harvesting/storage tanks (35%), terraces (33%), and Zai pits (17%) were most frequently mentioned. Finally, a total of eight practices were mentioned as serving integrated pest management functions on the farms visited in both ALLs. Eight practices were mentioned in Kiambu, while only three were reported in Makueni. The use of plant-based biopesticides was the most common practice in both ALLs, mentioned by 88 and 38% of farmers in Kiambu and Makueni, respectively. Further, farmers in Kiambu used repellent plants (25%) and practiced crop rotation (15%) and intercropping (15%) to manage pests.

In addition to specific host crops, several agroecological practices were implemented on the surveyed farms (Table 2). In Kiambu, practices applied to all crops included: agroforestry, compost, biogas sludge; while those applied mostly to vegetables were farmyard manure, mulching, multistorey kitchen gardens, plant-based biopesticides, sunken beds, traps, water harvesting and water recycling. The practices used for maize and beans were crop rotation, intercropping, mulching and farmyard manure, while the practices used for fruit trees were terraces and water harvesting. In contrast, in Makueni, the practices applied to all crops included: plant-based biopesticides, compost, terraces, zai pits and water recycling; while the practices applied mostly to vegetables were compost, crop rotation, farmyard manure, mulching, multistorey kitchen gardens, and plant-based biopesticides. The practices applied to cereals (maize, sorghum) and legumes (beans, cowpeas, pigeon peas, green grams) were agroforestry, compost, crop rotation, intercropping, mulching, and water harvesting; while the practices applied to fruit trees were: plant-based biopesticides and compost.

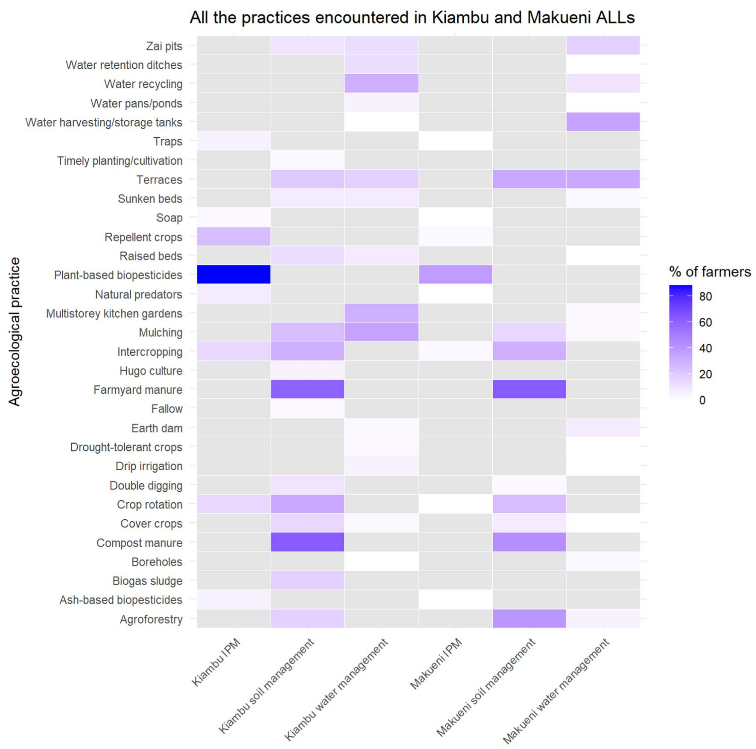

FIGURE 3
All the practices encountered in Kiambu and Makueni ALLs.

TABLE 2 Host crops associated with various agroecological practices from inventoried farms.

Kiambu ALL		Makueni ALL	
Agroecological practice	Host crops	Agroecological practice	Host crops
Agroforestry ($n = 2$)	All crops	Agroforestry ($n = 7$)	Agroforestry trees were mostly integrated within the cropland and grown together with all crops, including maize, beans, cowpeas, pigeon peas, and sorghum
Ash biopesticides ($n = 3$)	Mostly used in maize	N/A	N/A
Biogas sludge ($n = 1$)	Applied to all crops	N/A	N/A
Compost ($n = 13$)	Applied to all crops, including vegetables (kale, tomatoes, spinach), maize, beans, and Irish potatoes	Compost ($n = 11$)	Mainly used to grow a wide range of crops, including maize, black beans, beans, pigeon peas, potatoes, vegetables, and fruit trees.
Crop rotation ($n = 4$)	Crops mostly were maize, beans, and vegetables	Crop rotation ($n = 6$)	Crops mainly rotated were maize, beans, and vegetables.
Drought-resistant crops ($n = 1$)	Drought-tolerant crops planted include cassava, pigeon peas, sweet potatoes, and black beans		
Earth dams ($n = 1$)	N/A	Earth dams ($n = 2$)	Used to provide water to bananas, Napier grass, and pumpkins.
Farmyard manure ($n = 10$)	Mainly applied on vegetables, maize, and fruits such as strawberry	Farmyard manure ($n = 19$)	Mainly used on maize, beans, and vegetables.
Hugo culture ($n = 1$)	N/A	N/A	N/A
Intercropping ($n = 2$)	Maize was mostly intercropped with beans. Leguminous Calliandra spp. were also used for intercropping.	Intercropping ($n = 2$)	Intercropping was done between cowpeas, pigeon peas, beans, and maize.
Mulching ($n = 9$)	Mainly practiced on vegetables, but also on maize and beans	Mulching ($n = 3$)	Mulching was mostly done on maize, beans, pigeon peas, and cowpeas.
Multistorey kitchen gardens ($n = 8$)	Only vegetables are grown in multistorey gardens	Multistorey kitchen gardens ($n = 1$)	Used for vegetables, maize, and potatoes.
Plant-based biopesticides ($n = 16$)	Used to control pests on vegetables	Plant-based biopesticides ($n = 10$)	Applied on all crops, including fruit trees (oranges, mangoes, avocadoes); for controlling pests on trees such as *Grevillea robusta* and Senna spp.; and for vegetables, bananas, maize, beans, cowpeas, and pigeon peas.
Sunken beds ($n = 1$)	Vegetables	N/A	N/A
Terraces ($n = 2$)	Terraces were used for growing vegetables and leguminous fodder tree species (e.g., *Desmodium* and *Calliandra*)	Terraces (n = 14)	Used for growing all crops.
Traps ($n = 1$)	Mainly practiced on fruit trees and vegetables	N/A	N/A
Trenches ($n = 1$)	N/A	Zai pits ($n = 4$)	Used for growing all crops.
Water harvesting ($n = 7$)	Harvested water was mainly used for livestock, growing vegetables and fruits, and raising tree seedlings in nurseries	Water harvesting ($n = 8$)	Water harvested was used for growing vegetables, green gram, and maize.
Water recycling ($n = 6$)	Mostly used for growing vegetables	Water recycling ($n = 1$)	Recycled water was also used on all crops.

3.3 Context: performance and evaluation of inventoried soil, water, and IPM practices

After inventorying existing practices, respondents assessed the context in which the existing agroecological practices were implemented and their performance in the respective settings. Farmers were asked to document at least two practices that were of high importance to them. Thus, the in-depth contextual study does not provide information on all practices, but only on those that were prioritized.

3.3.1 Soil, water, and IPM practices included in additional contextual analysis

Respondents provided additional contextual information on a total of 26 of the 31 practices that cut across the three functions, of which 25 were inventoried in the Kiambu ALL, and 13 in the Makueni ALL (Figure 4). A total of 12 common practices were evaluated in both ALLs, with the main ones in Kiambu being plant-based biopesticides, compost manure, farmyard manure, mulching, and multistorey kitchen gardens. In Makueni, farmers mainly discussed farmyard manure, terraces, compost manure, plant-based biopesticides, water harvesting, and agroforestry. Zai pits were unique to Makueni farmers.

3.3.2 Benefits and functions associated with soil, water, and IPM practices

In their open-ended responses, respondents identified a total of 19 benefits and functions associated with the agroecological practices, which fell under 10 of the 13 agroecological principles across all the three broad operational principles for sustainable food systems (Figure 5). Eleven of the 19 benefits belonged to the operational principle of strengthening resilience agroecology, five benefits belonged to securing social equity and three benefits to improving resource efficiency.

Most of the benefits were associated with the broader operational principle of strengthening resilience, which includes agroecological principles 3 to 7. Under soil health, for example, biogas sludge (100%), compost manure (73%) and crop rotation (67%) were highly associated with improving soil fertility; while strip cropping, trenches, sunken beds (100%), terraces (79%) were perceived as beneficial in controlling soil erosion control; biogas sludge and traps (100%) were associated with reduced environmental pollution, while intercropping (50%) was seen as enhancing beneficial soil macrofauna. Several practices were said to contribute to the synergy principle through water conservation and water use efficiency, such as hugo culture, strip cropping, sunken beds, water pans and water retention ditches (100%) and water harvesting (88%); while agroforestry was said to contribute to microclimate regulation by providing shade (59%). The principle of economic diversification was mainly associated with practices that provide income

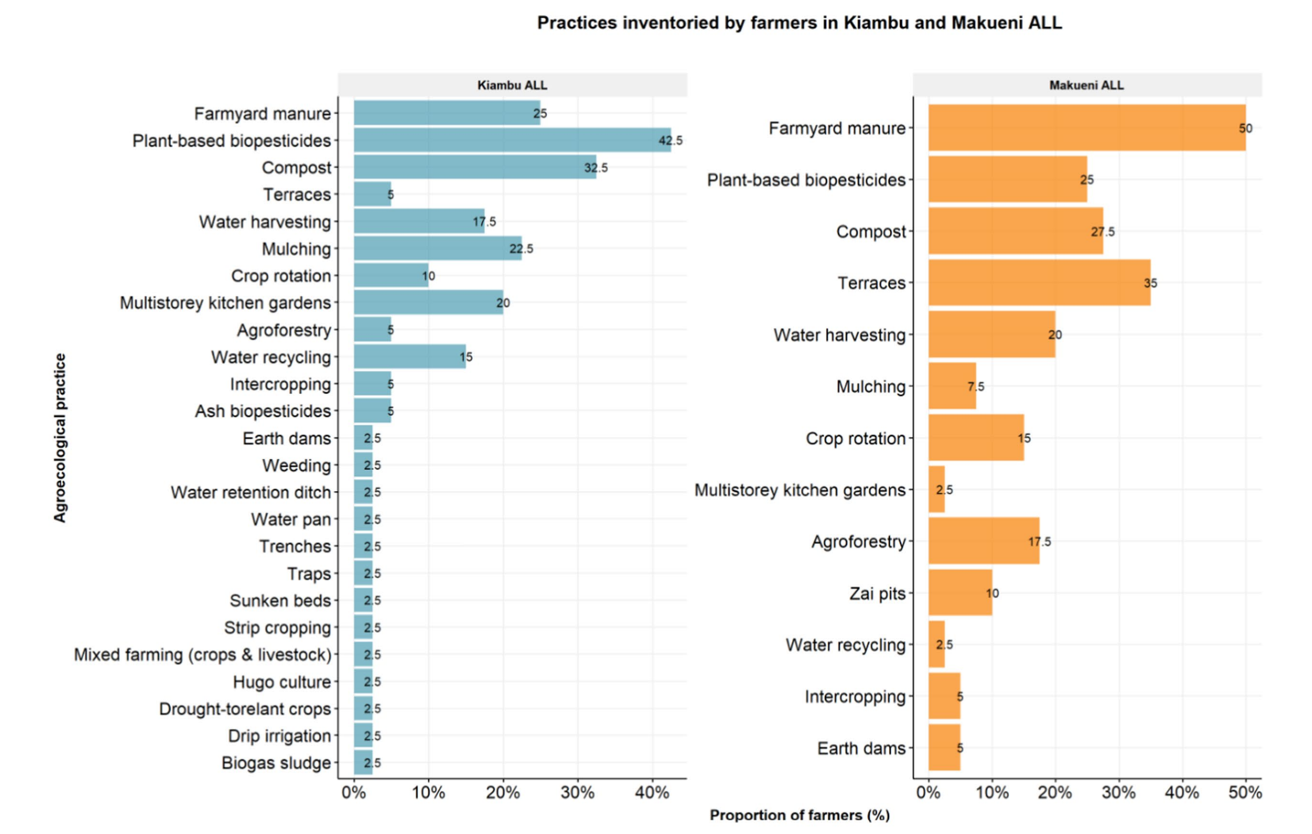

FIGURE 4
Practices inventoried by farmers in Kiambu and Makueni ALLs.

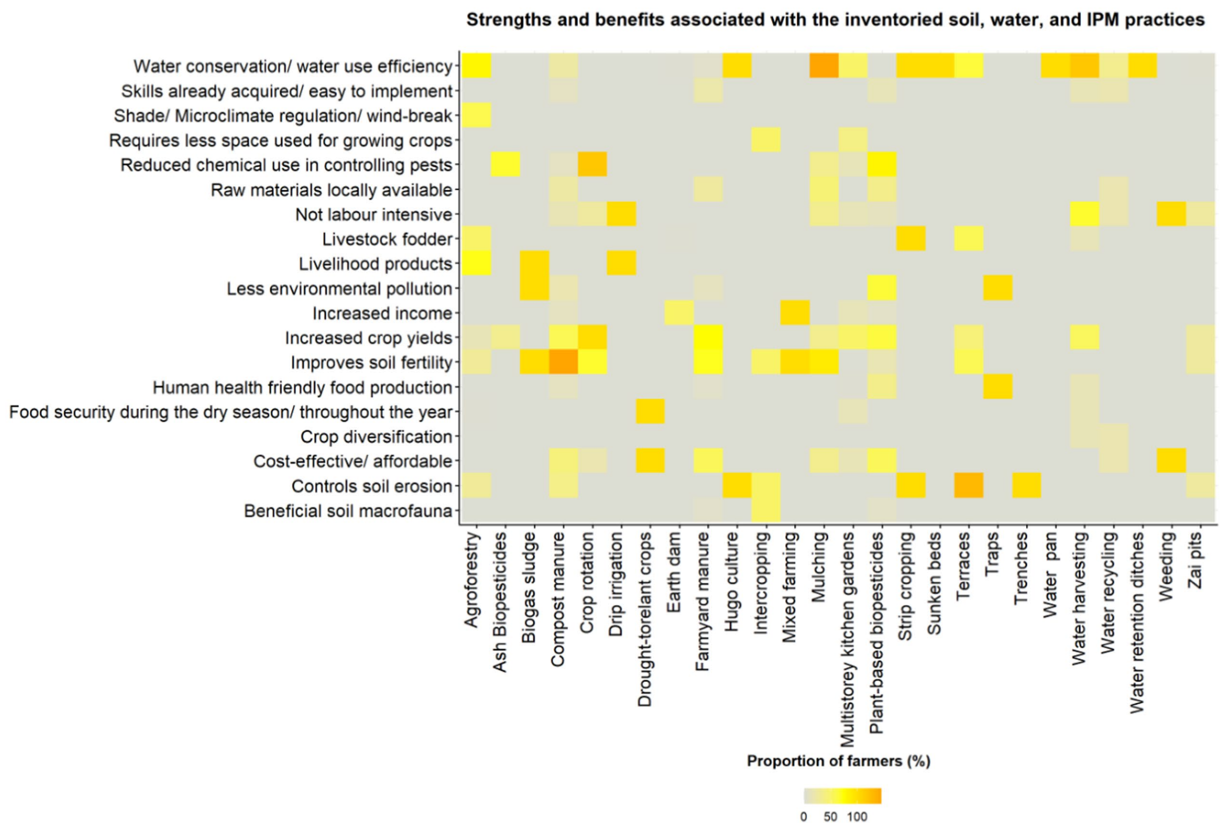

FIGURE 5
Benefits and strengths associated with inventoried soil, water and IPM agroecological practices.

and additional livelihood products diversification mainly biogas sludge, drip irrigation (100%), and agroforestry (71%). Improved animal health was associated with livestock fodder from strip cropping (100%), agroforestry and vegetation planted along terraces (50%).

Key benefits associated with the operational principle of securing social equity included: fairness through practices perceived as being cost effective such as weeding and planting of drought-tolerant crops (100%), farmyard manure (35%) and mulching (33%); while some practices were perceived as not being labor intensive such as drip irrigation, weeding (100%), water harvesting (34%) and mulching (33%). Social values and diets benefits included increased food security through drought-tolerant crops (100%); while practices associated with producing healthy and safe foods included the use of traps (100%) and plant-based biopesticides (18%). Finally, the operational principle on improving resource efficiency was mainly associated with input reduction through practices such as: reduced use of chemical pesticides through the use of ash-based biopesticides (67%), crop rotation (59%), and plant-based biopesticides (41%); while practices associated with the use of locally available raw materials that contribute to both input reduction and the use of local renewable resources included compost manure (23%), mulching (22%), plant-based biopesticides (18%), water recycling (17%), and farmyard manure (15%).

3.3.3 Challenges associated with soil, water, and IPM practices

In response to an open-ended question, farmers mentioned 13 challenges that limit the success or effectiveness of the soil, water and IPM practices they use (Figure 6). The most common challenges included: drought and water scarcity, being labor intensive, being costly and unaffordable, limited know-how, shortage of raw materials, being susceptibility to weather variability, and susceptibility to pest infestation. These challenges are discussed in subsequent sections. Drought and the water shortage was the most serious challenge, reported to affect numerous practices namely: multistorey kitchen gardens (100%) and agroforestry in both Makueni (71%) and Kiambu (50%); crop rotation (75%) and water harvesting (67%) in Kiambu; and mulching (67%) in Makueni.

Another challenge widely mentioned across both ALLs was that many practices were labor intensive. Some of the key practices perceived as labor intensive and time consuming were mentioned mainly in Kiambu and include construction and maintenance of structural practices such as terraces, trenches, sunken beds, and water retention ditches (100%), hugo culture (100%), multistorey gardens (100%) and weeding (100%), mulching and agroforestry (50%). In Makueni, fewer practices were perceived as labor intensive, including terraces (57%) and zai pits (50%). Some farmers reported having limited know-how of how to implement or do some practices, for example in Kiambu namely traps (100%), crop rotation (25%), and mulching (17%); while in Makueni, farmers had limited knowledge of compost manure (27%). Scarcity of raw materials was also mentioned especially in Makueni, namely for plant-based biopesticides (40%), mulching (33%), farmyard manure (26%), and compost (18%). In Makueni, pests were also reported in practices such as intercropping (50%), mulching (33%), compost (27%) and tree seedling establishment

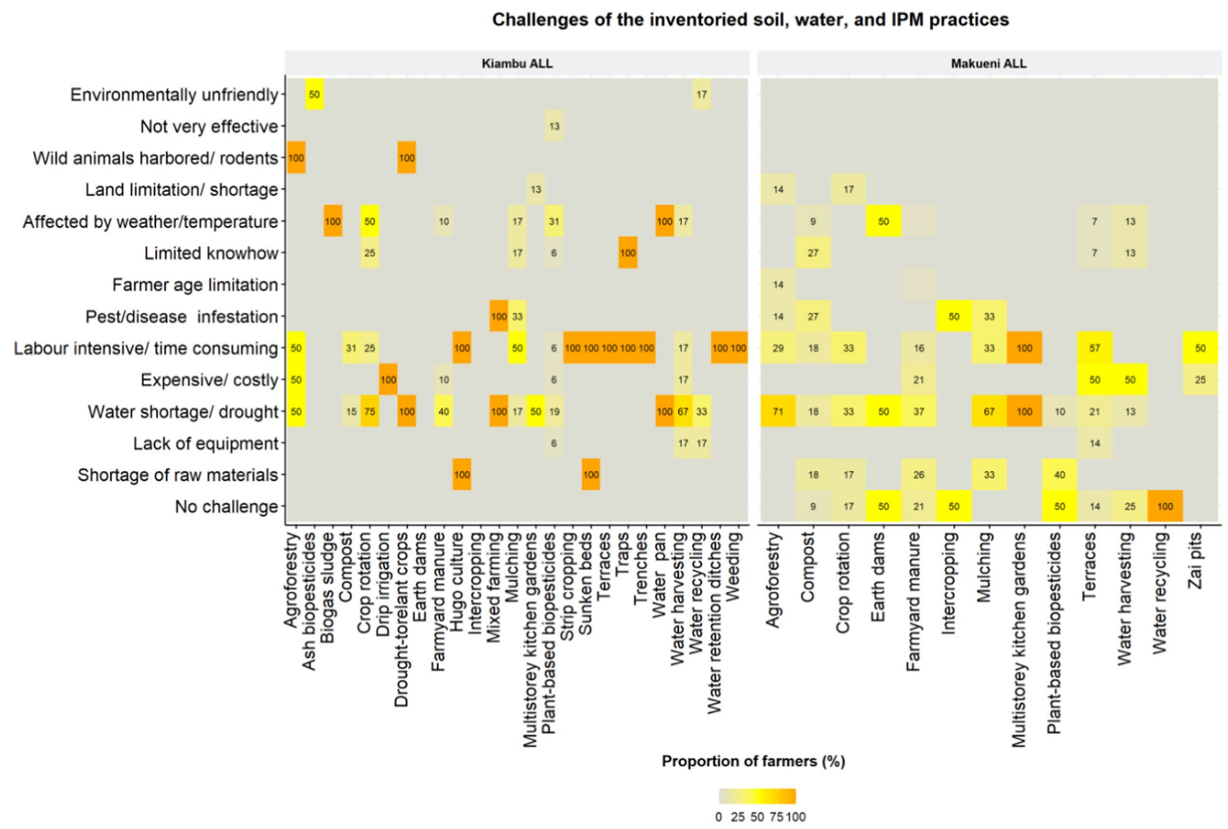

FIGURE 6
Challenges associated with the inventoried soil, water, and IPM agroecological practices.

in agroforestry (14%). In Kiambu, agroforestry (trees) was blamed for harboring wild animals (100%) that would consume the planted crops.

Another challenge mentioned in both ALLs was that some practices were considered as being costly and therefore farmers could not afford to implement them. Farmers identified four types of costs associated with the inventoried soil, water, and IPM practices: the cost of initial labor to implement the practices, the cost of purchasing raw materials and equipment, the cost of labor to maintain the practices, and the cost of transportation. The analysis showed that the highest costs in implementing the practices were associated with the initial labor required. In Kiambu, practices with high initial labor cost include agroforestry (100%), drought-tolerant crops (100%), intercropping (100%), terraces (100%), and water harvesting (86%) as shown in Figure 7. Maintenance labor costs were mostly incurred in crop rotation (25%), while the costs associated with raw material purchases included biogas sludge (100%), agroforestry (100%), drought-tolerant crops (100%), earth dams (100%), and multistorey kitchen gardens (100%). On the other hand, practices such as hugo culture (100%) and plant-based biopesticides (50%) were found to be the most cost-effective and affordable to install.

In the Makueni ALL, practices that were perceived to have the highest initial labor costs included earth dams, multistorey kitchen gardens and water recycling (100%), as shown in Figure 8. Practices incurring maintenance costs included crop rotation (50%) and agroforestry (43%), while practices that incurred high costs of purchasing raw materials included earth dams (100%), water harvesting (100%), and water recycling (100%). Water recycling further incurred transportation costs (100%). In addition, the analysis identified several practices that were perceived as easy to implement without the need for financial resources. These practices were plant-based biopesticides, mulching, crop rotation, farmyard manure (if sourced from own animals), and compost.

3.4 Farmer preferences in soil, water, and integrated pest management practices

Looking specifically at practices that the respondents would like to implement in the future, respondents in Makueni preferred to implement nine individual soil management practices (Figure 9A), with the most preferred ones being agroforestry (26%), compost manure (22%), and terraces and mulching (22%). Farmers preferred to implement 10 water management practices (Figure 9B), with the most preferred being agroforestry (26%), terraces (26%), earth dams (14%), and zai pits (11%). Farmers preferred to use six IPM practices (Figure 9C), with the most preferred being plant-based biopesticides (72%), crop rotation (15%), and intercropping (4%). In Kiambu, respondents preferred to implement 13 individual practices for soil management, with the most preferred ones being compost manure (20%), agroforestry (16%), crop rotation (14%) and mulching (11%) as shown in Figure 10A. Farmers preferred to implement 16 water management practices (Figure 10B), with the most preferred being water harvesting (34%), water recycling (13%), mulching (9%) and water pans (8%). Farmers preferred to implement nine IPM practices

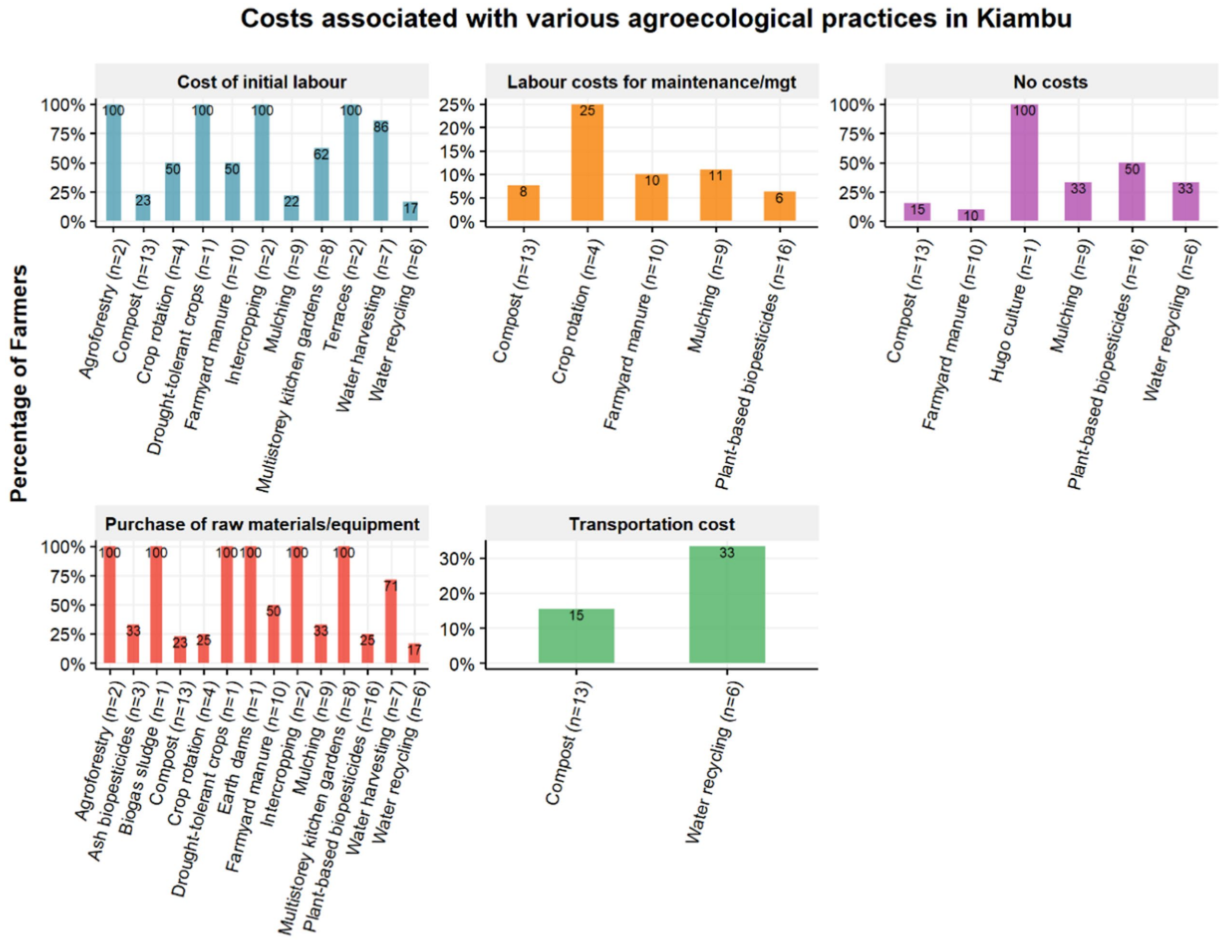

FIGURE 7
Costs associated with inventoried agroecological practices in Kiambu ALL.

(Figure 10C), with the most preferred being plant-based biopesticides (50%), ash-based biopesticides (17%), and traps (9%).

The assessment results showed that several practices were mentioned as preferred practices under two or all three focus areas. In Makueni, practices that could address all three functions were agroforestry (21%), and mulching (5%) as shown in Figure 11A. In addition, practices that were preferred to address both soil and water management needs were terraces (17%) and zai pits (6%). Practices mentioned under both soil management and IPM were crop rotation (6%) and intercropping (1%). On the other hand, in Kiambu, the preferred practices mentioned under both soil and water management were mulching (7%), multistorey gardens (4%), terraces (3%), and zai pits (2%); while the preferred practices for water management and IPM were water recycling (6%) and water pans (3%) as shown in Figure 11B.

3.5 Co-design and implementation of soil, water and IPM agroecological innovations

As mentioned previously, the co-design workshops consisted of seven steps (Figure 2). Resulting from steps 1, 2, and 3 of the co-design workshops, three specific innovative practices were chosen for farmer experimentation in each ALL. In the Kiambu ALL, participants selected to implement the integration of compost manure for soil management, mulching for water management and plant-based biopesticides for IPM (Table 3). In the Makueni ALL, participants selected farmyard manure for soil management, terraces for water management and plant-based biopesticides for IPM.

In step 4, farmers in both ALLs developed comprehensive crop selection criteria. Although conducted separately, participants identified five common criteria: the proposed crop had to be adaptable to local conditions, mature within the project period, have a readily available market, have low water requirements, and have high nutrient content. Additional unique criteria identified by Kiambu stakeholders included availability of seeds and planting materials, high yield potential, high susceptibility to pests for effective biopesticide testing, contribution to household food security and nutrition, economic significance to the local community, potential for value addition, and social acceptability. Stakeholders in Makueni identified additional unique criteria, namely the most popular and commonly used crops that most local farmers can adopt, crops that are disease resistant and tolerant, crops with local varieties, and crops that would be appropriate for the available space and farm sizes. As a result, in Makueni, due to limited space and farmers' familiarity with intercropping, farmers unanimously agreed to intercrop two test crops, namely maize (*Zea Mays*) and beans (*Phaseolus vulgaris L.*) to experiment with all three practices. Based on the above criteria, farmers in Kiambu agreed to

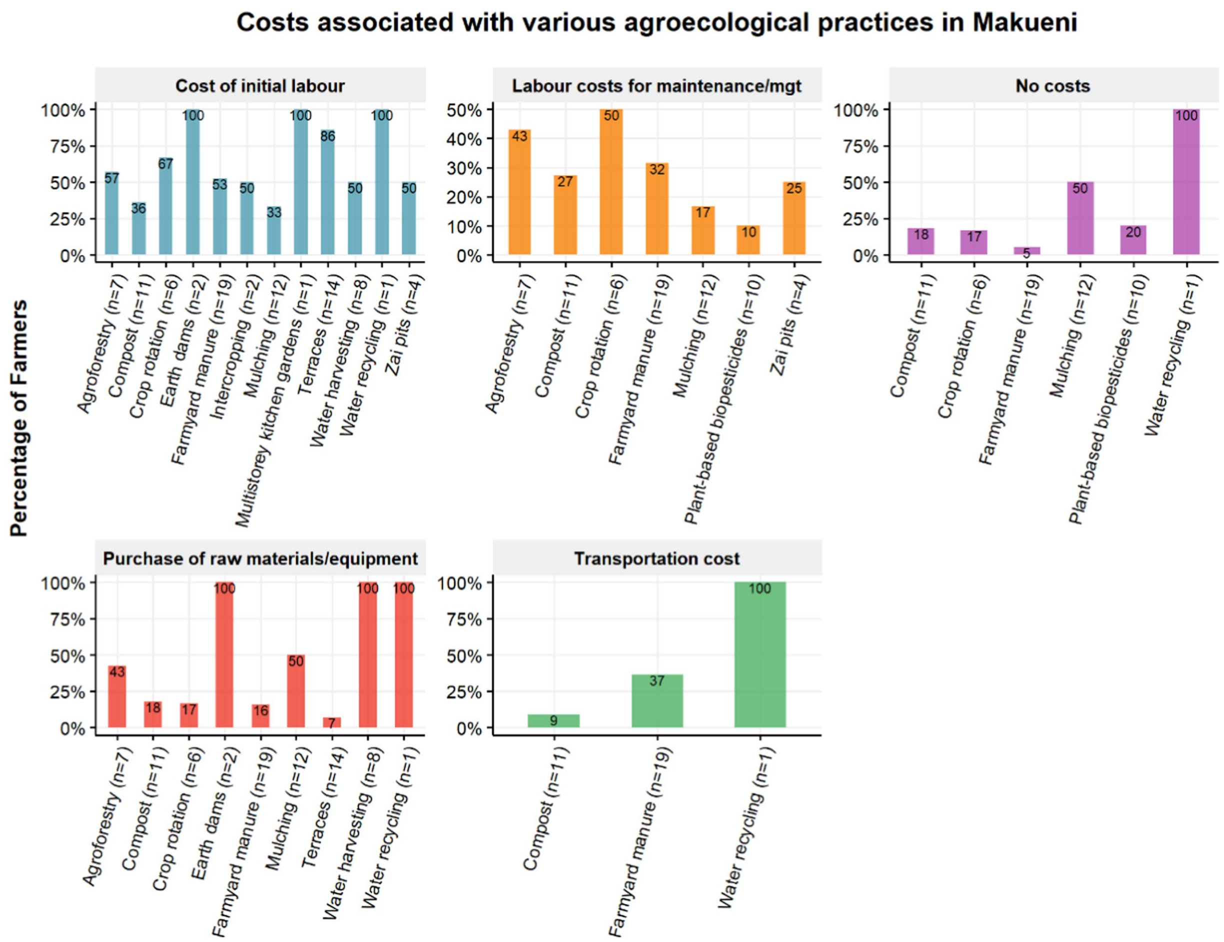

FIGURE 8
Costs associated with inventoried agroecological practices in Makueni ALL.

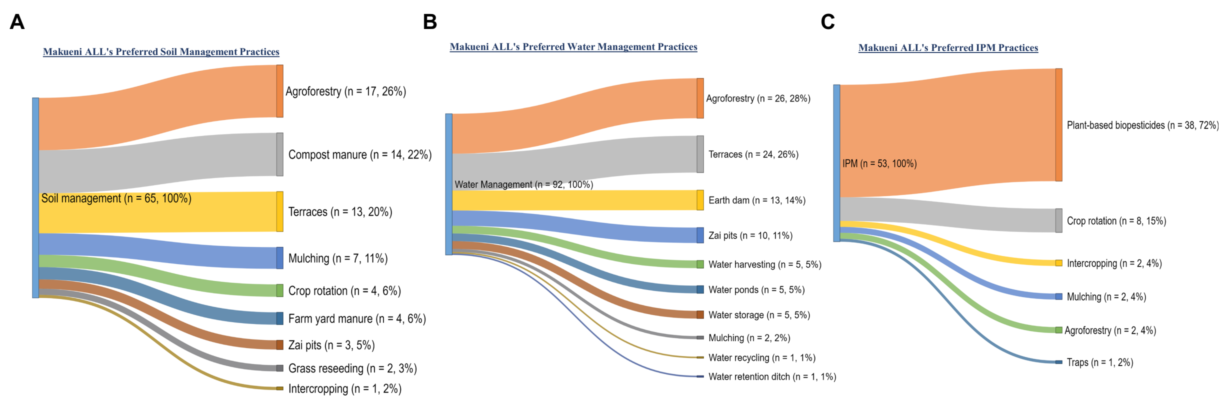

FIGURE 9
Agroecological practices preferred by farmers in Makueni ALL.

test the selected soil and water management practices on spinach (*Spinacia oleracea*), while cabbage (*Brassica oleracea* var. *capitata*) was chosen for IPM due to its high susceptibility to pests (Table 2).

In step 5, which involved defining the experimental design strategy, the participants decided to maintain their conventional practice on the control plots for each of the selected innovative practices to be tested, rather than adopting a uniform control protocol. It was decided that both the test plot for the agroecological innovation and the control plot would be located adjacent to each other. This proximity was essential to minimize any potential variation due to differences in soil fertility and landscape orientation by maintaining similar slope characteristics for both plots. Step 6 involved the development of monitoring protocols in which farmers deliberated on and agreed to measurable and observable criteria to be monitored and recorded at two-week intervals. These included

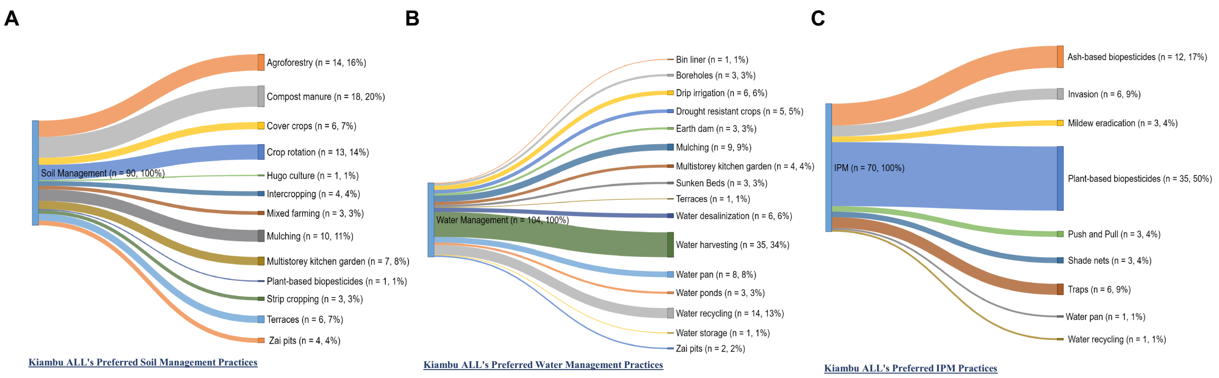

FIGURE 10
Agroecological practices preferred by farmers in Kiambu ALL.

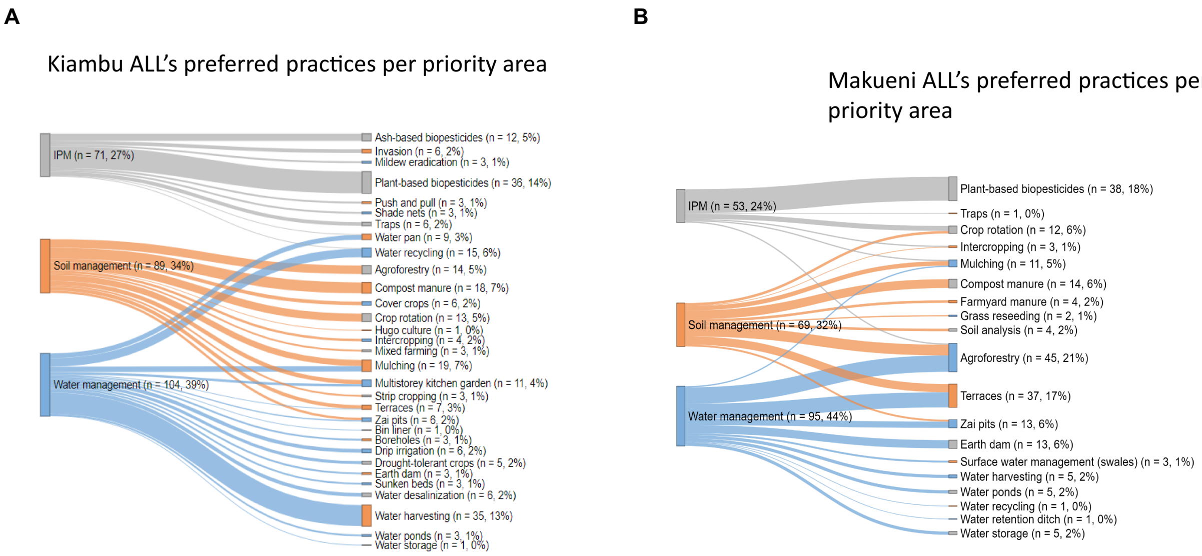

FIGURE 11
Preferred practices and their multiple functions identified in Makueni and Kiambu ALL.

quantifiable parameters such as crop yield, growth rate, leaf surface area, plant nutrient content and shelf life; and observable parameters such as plant color, plant vigor, size of produce or leaves/biomass, presence of pests and diseases, weed density and maturity period. Additional factors to be considered included production costs (including labor), marketability of the crop, and rainfall frequency, timing and intensity. The technical team recommended that data collection be conducted in two phases. First, initial baseline data was collected, which included soil sampling prior to land preparation and recording of the farm management history. Once established, the actual trial data were collected through three levels of monitoring and data collection by participating trial farmers, ALL host center staff, and Agroecology Initiative researchers.

Step 7 involved the joint definition of selection criteria for trial farmers, followed by their selection according to the criteria. In each ALL, participants first discussed the selection criteria for potentially eligible trial participants. In Kiambu, five criteria were identified, including: possession of physical assets, namely ownership of at least two plots of land measuring 6 m by 5 m; interest in participating in the trials; openness to innovation and adopting new practices; communication skills and willingness to share knowledge; and possession of desirable personal attributes, such as high integrity and hospitality. The Makueni participants also came up with five selection criteria for trial farmers, namely: ownership of a farm with at least one plot (5 m × 6 m) and having the necessary resources such as animal manure; willingness to carry out the trials; keeping timely records; willingness to host field day participants and researchers in their homes for measurements and demonstrations; and willingness to provide labor. Other criteria were openness to innovation and implementing new knowledge and skills; good communication skills; and positive personal attributes, namely strong family relationships with the community and no existing conflicts.

To make the process inclusive and fair, the trial participants decided to report back to their respective farmer groups, and then inform the Agroecology Initiative team on the selected persons, rather than deciding at the workshops. In the end, a total of 63 willing farmers were selected (30 in Kiambu, and 33 in Makueni; that is, 10+ farmers per focus area). In Makueni, 73% of the selected trial participants were female and 27% were male farmers, and in Kiambu, 50% were male and 50% were female farmers. Upon completion of the co-design workshops, Step 8 involved the Agroecology Initiative technical team conducting integrated technical trainings and

TABLE 3 Prioritization and final selection of agroecological practices to be implemented and associated test crops.

Prioritization and final selection of agroecological practices to be implemented and test crops					
Kiambu ALL			Makueni ALL		
Top 4 priority practices identified from the onfarm joint assessment	Top 3 priority practices identified during co-design workshops	Final agroecological practice and test crop selected for trial	Top 4 priority practices identified from the onfarm joint assessment	Top 3 priority practices identified during co-design workshops	Final agroecological practice and test crop selected for trial
Soil management					
1. Compost manure	1. Compost manure	1. Compost Test crop: spinach	1. Agroforestry	1. Farmyard manure	1. Farmyard manure test crops: maize and beans intercrop
2. Agroforestry	2. Agroforestry		2. Compost manure	2. Terraces	
3. Crop rotation	3. Mulching		3. Terraces	3. Compost manure	
4. Mulching			4. Mulching		
Water management					
1. Water harvesting	1. Water harvesting	1. Mulching test crop: spinach	1. Agroforestry	1. Farm ponds	1. Terraces crops: maize and beans intercrop
2. Water recycling	2. Mulching		2. Terraces	2. Terraces	
3. Mulching	3. Water pans		3. Earth dams	3. Water recycling	
4. Water pans			4. Zai pits		
Integrated pest management (IPM)					
1. Plant-based biopesticides	1. Repellent crops	1. Plant-based biopesticides test crop: cabbage	1. Plant-based biopesticides	1. Intercropping	1. Plant-based biopesticides crops: maize and beans intercrop
2. Ash-based biopesticides	2.Plant-based biopesticides		2. Intercropping	2. Plant-based biopesticides	
3. Repellent crops	3. Mulching		3. Crop rotation	3. Ash-based biopesticides	
4. Traps			4. Repellent crops		

practical field demonstrations for all three identified practices at the respective ALL host centers with all selected trial participants in each ALL. The trainings focused on sharing technical skills, with an additional focus on trial establishment and monitoring. To build capacity as broadly as possible, all 63 trial participants were trained in all three practices in integrated three-day workshops facilitated by the Agroecology Initiative team and technical experts. This was followed by Step 9, the trial establishment on farms. Farmers were given hard copies of the co-designed monitoring sheets to be able to record observations and crop performance (using the indicators listed in Step 6) to build their observation and record keeping skills and knowledge, which are critical for assessing the performance of cropping systems over time and for timely adaptation of agroecological practices based on contextual needs to achieve optimal crop production. In Step 10, intra-ALL and inter-ALL farmer-to-farmer knowledge exchanges were organized to foster peer learning, joint reflection, strengthen social networks among farmers, which, in turn, support the development and refinement of sustainable and contextualized farmer-led agricultural innovations.

4 Discussion

4.1 Understanding household dynamics in agroecological design

The results showed distinct differences in land size, gender dynamics and other household demographics between the Makueni and Kiambu ALLs, highlighting the importance of considering household characteristics when designing agroecological practices (Liani et al., 2023). For example, there were differences in average household land size in the two ALLs (1.73 ha in Makueni and 0.84 ha in Kiambu), which may have influenced the most planted crops beyond agroclimatic factors (Manjunatha et al., 2013). While farmers in Makueni mainly planted maize, beans, cowpeas and pigeon peas, 75% of respondents in Kiambu planted vegetables in addition to maize, beans, and potatoes. This can be interpreted as farmers in Makueni adopting more traditional farming practices compared to more intensive and market-oriented practices in Kiambu. This has been observed elsewhere, with additional influencing factors being access to ready markets, access to economic resources and, of course, agro-climatic conditions (Esquivel et al., 2021).

The average age of farmers in both ALLs was 56 years, highlighting the generational continuity of farming, with older farmers dominating. Older age may have posed a challenge in terms of farmers' inability to engage in labor-intensive agricultural activities (Benin et al., 2004), as evidenced by the fact that several practices, including terraces, zai pits, mulching and multistorey kitchen gardens were described as labor-intensive. This emphasizes the need to design and implement agroecological practices that are less labor intensive and easy to implement (Mekuria et al., 2022); or to find innovative ways to adapt existing practices to reduce labor requirements and enable effective and sustainable adoption of such interventions. The average age of our respondents may also indicate that fewer youths are engaging in agricultural activities. This is particularly true as more youth in sub-Saharan Africa migrate to urban areas in search of paid labor (Castañeda-Navarrete, 2021; Crossland et al., 2021a); although our results may partly be related to the sampling framework and the relatively small sample size overall.

Furthermore, although 72% of households surveyed in both ALLs were male headed, the majority of farmers interviewed (70%) were women. The low number of men interviewed was mainly due to factors such as men migrating to towns in search of better livelihood opportunities and engaging in off-farm activities such as petty trading (Crossland et al., 2021b; Greiner and Sakdapolrak, 2013). In Kenya, as in most sub-Saharan countries, even though agricultural activities are mostly undertaken by women and low agricultural productivity is mostly experienced by women (Awiti, 2022), men typically hold most of the land and are the main decision makers (Errico, 2021; Holden and Tilahun, 2020). Therefore, women have limited or no control or access to the productive resources on which agricultural activities depend (Valencia et al., 2021). To creatively address this potential conflict, during the co-design workshops, both men and women were encouraged to participate, and they were sensitized on the need for collective decision making and participation in agricultural innovation design, implementation and management (Madzorera et al., 2023; Sariyev et al., 2021). Other approaches that have been used to close the gender gap include implementing policy reforms that are gender-inclusive, transformative and responsive, and that take into account the unique gender differences that exist such as differences in gender roles, knowledge, skills, experiences, constraints and opportunities, access to resources, rights to resources and decision-making (Lopez et al., 2022; McGuire et al., 2022). Examples of practical approaches include promoting equity by empowering women with skills and access to economic resources to improve the food security outcomes of their farming activities (Farnworth et al., 2023; Shrestha et al., 2023). Other approaches relevant to the sub-Saharan context include involving both men and women, or husbands and wives, in the selection, design, and implementation of agroecological practices so that innovations to have more gender-responsive and inclusive outcomes (Crossland et al., 2021a; Paudyal et al., 2019).

4.2 Farmers' knowledge and priorities inform co-design of multifunctional and inclusive agroecological practices

The results showed that farmers identified 31 practices (29 in Kiambu and 13 in Makueni), of which 18 and 13 were unique to Kiambu and Makueni, respectively. The results further showed that farmers preferred a diverse range of 26 soil, water and IPM agroecological practices that they were interested in adopting and/or maintaining on their farms, with more practices mentioned in Kiambu compared to Makueni. This highlights the underlying high heterogeneity of the farming systems and the different needs and priorities of farmers (Kihoro et al., 2021; Vanlauwe et al., 2014). Furthermore, while Makueni was dominated by farmyard manure, terraces, and water harvesting techniques reflecting a greater emphasis on soil conservation and water scarcity, Kiambu was dominated by organic input-based practices mainly plant-based biopesticides, compost manure, and mulching. The contextual variations highlight the need to understand the local context and thus tailor agroecological interventions to the context (Coe et al., 2014; Mutemi et al., 2017).

This study also found that farmers prefer agroecological practices that address multiple functions of soil, water and integrated pest management on their farms. For example, in Makueni, agroforestry and mulching were highlighted as preferred practices that address all three functions of soil, water and integrated pest management simultaneously. However, farmers preferred terraces and zai pits for meeting the soil and water management functions; and crop rotation and intercropping serving both soil management and pest management functions, in line with (Lasco et al., 2014). In Kiambu, farmers' preference for compost manure and water harvesting in meeting their soil and water management needs is in line with previous studies that have demonstrated the benefits of practices that enhance water use efficiency and organic soil amendments (Adugna, 2016). These findings are consistent with the concept of multifunctional and multipurpose agriculture (Sivini and Vitale, 2023), and highlight the need to promote agroecological practices that serve multiple functions through synergies and complementary ecological interactions (Stefanovic et al., 2020).

Despite the inventoried agroecological practices contributing to multiple benefits, farmers identified only 20 distinct benefits that aligned with 10 of the 13 agroecology principles they derived, highlighting the need for awareness raising as part of co-designing agroecological practices. The benefits were derived from open-ended questions. Open-ended formats allow respondents to express their views (Reja et al., 2003). In terms of the three broader operational principles of agroecological sustainable food systems, 11 benefits reported by farmers fall under the seven agroecological principles that are categorized under the broader principle of strengthening resilience (Wezel et al., 2020). Consistent with the literature, many benefits were associated with the soil health principle, which received significant attention, with practices such as compost manure and crop rotation understood as contributing to increased soil fertility; terraces and strip cropping to soil erosion control while intercropping was viewed as enhancing beneficial soil macrofauna and promoting biodiversity (Singh et al., 2023). Contrary to existing literature, majority of farmers did not associate practices such as mulching and agroforestry with improving soil fertility or controlling soil erosion (Nzeyimana et al., 2013; Rosenstock et al., 2014).

Other practices were found to be beneficial in strengthening resilience by creating synergies such as conserving soil water, including as farmyard manure, hugo culture, sunken beds, mulching and strip cultivation, in line with Ndiso et al. (2018), while agroforestry was found to regulating microclimate, improve animal health through fodder and provide livelihood products (Gicheru et al., 2004; Mbow et al., 2014; Muthuri et al., 2023). Furthermore, resilience is further enhanced by increasing the diversity and abundance of such agroecological practices (Gachuiri et al., 2017; Magaju et al., 2020). Few farmers mentioned benefits related to the principle of economic diversification, which may indicate low knowledge, productivity or diversity of existing practices (van Zonneveld et al., 2020). Overall, only a few practices such as farmyard manure, plant-based biopesticides and water recycling were associated with the knowledge co-creation principle, where farmers reported already having and sharing existing knowledge about their implementation and performance amongst themselves. This highlights the need to address knowledge gaps on how to operationalize agroecological principles through specific agroecological practices as a prerequisite for promoting their adoption on farms (Bellamy and Ioris, 2017; Mottet et al., 2020). Doing so can increase their adoption rate, performance, and sustainability (Dumont et al., 2021).

Second, benefits related to securing social equity were evident as reported by farmers. For example, the fairness principle was addressed by many farmers who used organic material amendments that were low-cost and not labor-intensive, such as mulching and farmyard manure, in line with Maja et al. (2017). On the other hand, other practices, especially structural ones such as terraces, sunken-beds and water-retention ditches, were considered costly and unaffordable due to farmers' resource constraints, as well as labor intensive. This contrasts with other studies that have observed that farmers' perception of interventions being costly discourages their adoption due to the risks and uncertainties of outcomes against financial investments (Barry et al., 2021; Greiner et al., 2009). Cumulatively, these characteristics discourage farmers from widely adopting such innovations and threaten the long-term sustainability and success of agroecological practices (Panpatte and Jhala, 2019). Furthermore, in line with the literature, the social values and diets principle was addressed through practices that were perceived to promote food production in a human health-friendly manner, such as the use of plant-based biopesticides and physical traps to control pests (Rana et al., 2019), and achieving food security throughout the year by planting drought-tolerant crops (Atube et al., 2021). Such agroecological practices play a role in ensuring access to dietary diversity, thereby promoting nutritional security (Chakona and Shackleton, 2018; Kansanga et al., 2021) and increased access to multiple ecological services (Dissanayaka et al., 2023). These findings are consistent with previous studies highlighting the social dimensions of agroecology, emphasizing its potential to address inequalities and enhance the well-being of local communities (Gliessman, 2018).

Finally, three benefits related to promoting resource efficiency were identified. These mainly focused on input reduction through practices that were considered to reduce chemical use, such as ash-based biopesticides, plant-based biopesticides, compost manure and crop rotation. It has been reported that chemical use leads to multiple harmful forms of pollution, not only to soil/ land, but also to water bodies and air (Rana et al., 2019). This is in line with the broader need to move towards more sustainable and environmentally friendly agricultural systems (Pretty, 2009). In addition, practices such as compost manure and mulching utilize locally available materials in line with the principle of recycling. However, some studies indicate that for soil nutrient recycling to be effective and sustainable, there is a need for diversity and a wide range of organic input sources to meet the many soil macro- and micro-nutrients regularly required by crops (Falconnier et al., 2023). This implies the need to build farmer capacity and promote diverse agroecological practices to holistically meet these needs, thereby improving and sustaining crop productivity.

4.3 Agroecological transitions require addressing existing contextual limitations to soil, water and pest management

Constraints to agroecological transition are diverse and vary across contexts, underscoring the need to document and address constraints before or during the implementation of agroecological practices. Farmers identified numerous challenges that currently limit the successful implementation of agroecological soil, water, and integrated pest management practices, drawing attention to the complex and multifaceted nature of the transition required for such farming systems (Mekuria et al., 2022). One of the major challenges identified was the recurrent drought and water scarcity, which constrained practices more than two-thirds of all inventoried practices in both Kiambu and Makueni. This finding underscores the vulnerability of agricultural systems to climate change and highlights the need to design resilient and adaptive water conservation innovations (Lobell et al., 2011; Mpala and Simatele, 2023), as well as the general need to understand contextual constraints when designing interventions (Abu-Elsamen et al., 2019; Andersson and D'Souza, 2014).

Other examples include the importance of using appropriate mulching materials in the right proportions, which not only reduce soil evapotranspiration and control weeds that compete with crops for water, but also decrease soil compaction through increased aeration. This increases the retention of green water in the macro-aggregates, making it available for crop growth over a longer period of time (Chukalla et al., 2015). Another example is the use of shade netting structures to control water evaporation from water storage structures such as earth dams, trenches, water pans and water retention ditches (Craig et al., 2005; Muriuki et al., 2014). In this way, the harvested water can last longer and can even be used for irrigation to bridge the gap between one rainy season and the next.

In addition, the labor-intensive nature of many practices poses a significant barrier to adoption and scalability, as reported by farmers in both ALLs, highlighting the importance of considering labor constraints in the design and implementation of agroecological practices. Examples include designing and experimenting with different designs and variations of practices, such as different sizes of zai pits, which are labor intensive (Crossland et al., 2021b). Furthermore, some practices were perceived to be costly and unaffordable for resource-constrained households, which discourages farmers from adopting such practices (Bizoza and Graaff, 2012; Gillian et al., 2016). We found that the two most significant costs incurred were the initial labor costs of implementing practices such as terraces and water harvesting, and the cost of purchasing raw materials and equipment, in line with Mouratiadou et al. (2024). Economic barriers to the adoption of agroecological practices have been widely reported, especially for resource-constrained households (Yagi and Garrod, 2018). Some approaches to overcome financial barriers include the use of innovations that promote efficient use of locally available materials (Piñeiro et al., 2020). In addition, farmers have identified cost-effective and affordable practices such as mulching, suggesting potential opportunities to promote accessible and sustainable solutions that align with farmers' financial capabilities (Carolan, 2018).

The constraints of scarcity of raw materials and inputs identified by farmers point to the need to address the systemic drivers and promote circular economy that reduces the inflow of inputs while ensuring increased recycling and reuse of locally generated raw materials, wastes and residues for practices such as mulching, composting, farmyard manure and gray water (Velasco-Muñoz et al., 2021). This includes exploring innovations such as the use of biochar to improve soil fertility, structure and aeration, to increase soil water-holding capacity, and control pest and diseases (Alkharabsheh et al., 2021; Safaei Khorram et al., 2016). Pest infestation was also mentioned to affect multiple practices such as mulching, agroforestry and compost, further highlighting the need for a systems approach that integrates different pest management strategies within existing practices, such as the use of clean raw materials, coupled with biological, cultural and mechanical practices (Dara, 2019; Rathee et al., 2018). The widespread challenge of limited knowledge on the benefits and scientific mechanisms and functions of different agroecological practices underscores the need for co-design processes that address knowledge gaps through capacity building and the establishment of on-farm demonstrations for co-learning and showcasing of agroecological best practices (Adamsone-Fiskovica and Grivins, 2022). Overall, addressing the above challenges requires a multifaceted and holistic approach that integrates integration of local knowledge with technical knowledge.

4.4 Supporting evidence-based stakeholder engagement and co-design: employing a methodical approach for selecting and testing agroecological innovations

As mentioned above, the rapid innovation assessment was conducted in the context of a broader co-design cycle, the main objective of which was to test innovative agroecological practices through trials on farmers' fields in both ALLs (Fuchs et al., 2023b). The actual co-design design workshops were highly methodical and followed a clear sequence, and included different food system actors, including purposively selected male and female farmers from 15 farmer groups per ALL.

As described, the co-design workshops themselves involved seven steps (Figure 2). The results of the innovation assessment were presented to participants in step 1. To render insights into options, contexts, and preferences more accessible and intelligible for participants, we prepared posters for each of the top three to five practices per focus areas to visually support the data sharing. The posters provided simple overviews of the main results drawn from the innovation assessment. This helped participants in the identification, selection, and contextual adaptation of appropriate and suitable innovative practices. Addressing farmers' needs, priorities and preferences has been reported to be a major driver of adoption of agri-food innovations (Antwi-Agyei et al., 2021; Fuchs et al., 2023b; Roussy et al., 2019).

These steps included identifying selection criteria for the innovations and the host crops. Other steps involved co-designing participatory trial protocols to ensure that participating farmers document the performance of their trials and play the role of actual farmer-scientists. Participants then discussed selection criteria for participating farmers that would ensure proper implementation, and documentation, while recognizing their responsibilities to their community to ensure that the experience and knowledge gained is shared with others. The final step involved the establishment of the trials, where the Agroecology Initiative technical team conducted integrated technical trainings and demonstrations for all three identified practices at the respective ALL host centers with all selected trial participants in each ALL. The training focused on sharing technical skills, with an additional focus on trial establishment and monitoring. In order to strengthen capacity as broadly as possible, all 30 trial participants per ALL were trained in all three practices in integrated three-day workshops facilitated by the Agroecology Initiative team and technical experts. This was followed by trial implementation on farms, accompanied by regular monitoring, co-learning and adaptation of the agroecological practices to suit the local context. The flexibility granted to farmers to implement, observe, experiment with and adapt agroecological practices to suit their context has been reported as a key driver for continued adoption of innovations (Falconnier et al., 2017).

The process of selecting, prioritizing and co-designing agroecological innovations for implementation involved a systematic approach aimed at ensuring diverse stakeholder engagement and representation (Fraser et al., 2006; Pagella and Sinclair, 2014; Triomphe et al., 2022). Through purposive selection (Tongco, 2007), participants were chosen to ensure broad representation, promote inclusive decision-making, and enhance the relevance of the selected innovations to local contexts (Jones-Garcia and Krishna, 2021). Each workshop served as a platform for stakeholders to deliberate on the most suitable and desired options to be tested through monitored trials, thereby facilitating knowledge exchange and consensus building among participants. The co-design workshops encompassed seven sequential steps designed to systematically guide stakeholders through the process of innovation selection and co-design process. This provided the basis for subsequent discussions on preferred innovative practices, informed by farmers' expressed preferences and priorities (Gliessman, 2018). Subsequent steps focused on the selection of agroecological innovations for trial testing, with participants collaboratively narrowing down options based on the priority farmer preference list generated in earlier stages of the process. The culmination of this deliberative process resulted in the unanimous selection of practices to be implemented, tailored to the specific needs and contexts of each ALL.

The joint definition of criteria for selecting test crops to accompany the chosen innovations illustrates the importance of co-design (Dawson et al., 2008). Common criteria that motivated the selection of crops in both ALLs included adaptability to local conditions, high nutritional content and high economic value and readily available markets. Similar criteria have been reported elsewhere as motivating farmers to adopt innovations (Ahmed and Tetteh Anang, 2019; Singha et al., 2012). In Kiambu, these included seed availability and household food security, while in Makueni, the focus was on crop disease resistance and local farmers' familiarity. This approach highlights the need to understand and consider farmers' motivations, both intrinsic and extrinsic, when designing agrifood innovations, as this further increases the likelihood that they will adopt and sustain such innovations (Greiner et al., 2009; Jambo et al., 2019). The decision to intercrop maize and beans in Makueni reflects a pragmatic approach to maximize space use and leverage farmers' existing knowledge and practices (Altieri, 1999). Such tailored strategies for crop selection demonstrate a nuanced understanding of local agricultural contexts and participants' priorities.

In discussing the experimental design, participants emphasized the importance of positioning control plots adjacent to innovative practice plots to minimize potential variation in soil fertility and environmental factors. This approach ensures robust comparisons between treatment and control plots, thereby increasing the reliability and validity of experimental results (Pretty et al., 2003). The co-design of participatory monitoring protocols allowed combining variables that are of interest to farmers and those required by the research more broadly (Parwada et al., 2022). The monitoring sheets containing the crop performance parameters to be monitored (including when, how and why to monitor) are used for simultaneous trial monitoring by farmers, our research team, and the ALL-host centers. Participatory monitoring aims to build their capacity to sustain agroecological best practices in the future and to take timely and effective remedial actions to improve overall performance through the practical skills they gain from the process (Junge et al., 2009; Rossi et al., 2023). This supports their transformation into farmer-scientists as they can experiment with different management practices while monitoring crop progress and performance based on the pre-defined parameters (Marchant et al., 2019; Oliver et al., 2010) to identify the contextual factors that enhance or limit crop performance. Collaborative monitoring also ensures that challenges are identified early and addressed quickly (González-Orozco et al., 2023). This is an important step towards agroecological transition and promotes a sense of ownership of the innovations by implementers, which supports the adoption rate, success, and sustainability of such agroecological practices (Li et al., 2019; Sapbamrer and Thammachai, 2021). It also ensures that farmers' local knowledge is fully utilized to adapt practices to address local challenges (Puppo et al., 2023). Finally, the joint definition of selection criteria for trial participants, and their participatory selection, is likely to strengthen participants' sense of responsibility and duty to their fellow farmers, and also likely to strengthen demand from other farmers for knowledge exchange (Fuchs et al., 2019b). Farmer-to-farmer extension and other co-learning opportunities have been heralded as an effective approach for scaling up agroecological practices (Gliessman, 2018). Moreover, collective learning and shared knowledge systems, coupled with the shared commitment, are not only a catalyst for the successful adoption of innovations (Waarts et al., 2002), but also for diffusion and scaling of innovations (Chen and Li, 2022).

By integrating farmer knowledge and preferences into decision-making processes, the co-design approach held a promise for promoting sustainable agricultural transitions rooted in local expertise and community empowerment. This transdisciplinary approach aimed to integrate farmer preferences and knowledge with scientific knowledge to develop and test agroecological practices that are locally understood, relevant, appropriate and inclusive (HLPE, 2019; Sinclair et al., 2019). This participatory approach is consistent with the principles of co-design, which emphasize the involvement of diverse stakeholders in decision-making processes to ensure the relevance and feasibility of interventions and helped to create a sense of ownership of the co-design process and outcomes by all stakeholders (Dumont et al., 2017; Fuchs et al., 2019b).

5 Conclusion

The Agroecology Initiative team facilitated a comprehensive co-design process to support on-farm experimentation with and generation of evidence on the performance of contextually suitable innovative agroecological practices in the Kenyan ALLs in Kiambu and Makueni counties. The team conducted a rapid innovation assessment to gain insights into existing innovation options, contexts and preferences. This assessment informed the team's scientific input to the actual co-design workshops where participants co-created innovative practices, experimental designs, and selection criteria for participating farmers. The collaborative assessment identified and evaluated the existing agroecological practices in three priority areas, namely soil management, water management, and integrated pest management. The assessment mapped 31 agroecological practices that were identified on respondents' fields in both ALLs, with 29 practices found in Kiambu and 18 practices being inventoried in and Makueni. The assessment of the inventoried options highlighted the heterogeneity of the socio-economic and biophysical contexts between the Kiambu and Makueni ALLs, which influenced the performance of each practice. Respondents expressed a preference for a total of 31 practices, of which 77% were associated with one of the three focus areas (soil management, water management, or IPM), while 33% were assigned multiple functions in at least two of the three areas simultaneously.

Overall, the assessment provided insights into existing options, their contextual evaluation, and preferences for both function-specific and multifunctional practices. The assessment also highlighted gaps and potential opportunities for the improvement and contextual adaptation of specific innovation practices to enhance their performance. In addition, the process itself allowed participants to introduce and discuss potential additional practices that had not yet been popularized in the ALLs that had been tested and implemented elsewhere in a similar context. The methodical and iterative co-design cycle allowed for the mobilization of different types and sources of knowledge and fostered the co-creation of criteria, priorities, and the joint selection of options, experimental designs, monitoring protocols and participants. This collaborative and structured approach responds to the importance of understanding and considering farmers' options, context and preferences in co-designing locally relevant and inclusive agroecological practices to promote greater adoption, successful implementation and long-term sustainability of agroecological practices, thereby promoting sustainable agrifood systems.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found at: https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/8V4G7M.

Ethics statement

The studies involving humans were approved by CIFOR-ICRAF research ethics committee. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

AK: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. PB: Conceptualization, Investigation, Methodology, Validation, Visualization, Writing – review & editing. BA: Conceptualization, Formal analysis, Validation, Visualization, Writing – review & editing. HK: Conceptualization, Methodology, Writing

– review & editing. MS: Conceptualization, Methodology, Writing – review & editing. PG: Conceptualization, Methodology, Writing – review & editing. MM: Conceptualization, Methodology, Writing – review & editing. LO: Conceptualization, Formal analysis, Writing – review & editing. WN: Conceptualization, Investigation, Methodology, Writing – review & editing. NS: Conceptualization, Project administration, Validation, Writing – review & editing. EK: Conceptualization, Project administration, Validation, Writing – review & editing. LF: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. This work was supported and funded by the Consultative Group on International Agricultural Research (CGIAR) through the Agroecology Initiative: Transforming Food, Land, and Water Systems Across the Global South project. Grant Number: CGIAR Initiative on Agroecology (INIT-31).

Acknowledgments

This study was conducted jointly with partner and host organizations and farmers. We are grateful for the support, team effort, and commitment of all persons involved. We thank our partners from the Drylands Natural Resources Centre (DNRC), a locally registered non-government organization (NGO) whose primary goal is to promote sustainable development of resources of the drylands regions of Kenya, and from Community Sustainable Agriculture Healthy Environmental Program (CSHEP), a registered community-based organization (CBO) focused on training small-scale farmers on agroecological and organic practices in Ndeiya, Kiambu County; and the Participatory Ecological Land Use Management (PELUM Kenya) team, and specifically Patrick Ngunjiri Kihoro, Zonal coordinator for Lower Eastern and Coast zone, for taking part in the data collection exercise and codesign workshops. Lastly, we thank Victor Mutugi (CIFOR-ICRAF) for supporting with data analysis for some results.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 03 October 2024
DOI 10.3389/fsufs.2024.1456991

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OPEN ACCESS

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RECEIVED 29 June 2024
ACCEPTED 19 September 2024
PUBLISHED 03 October 2024

CITATION
Yeo ML and Keske CM (2024) From profitability to trust: factors shaping digital agriculture adoption.
Front. Sustain. Food Syst. 8:1456991.
doi: 10.3389/fsufs.2024.1456991

From profitability to trust: factors shaping digital agriculture adoption

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Digital agriculture supports farmers' decision making to improve productivity and profitability. However, adoption of digital technology is uneven. Through interviews with 21 medium acreage almond growers and crop consultants in California's Central Valley, we examine barriers to adoption through the lens of technology acceptance models, Technology Acceptance Model (TAM-3) and Unified Theory of Acceptance and Use of Technology (UTAUT-2). Not surprisingly, farmers are willing to adopt technology when profitability and ease of use are shown, with economic returns (either anticipated or demonstrated) from the technology investment serving as the primary factor influencing adoption. Trust operates as a moderating factor to the desire for economic returns that influences adoption. There may be trust, or lack of trust, in technology performance or in the advisors who recommend it. Producer trust is affected by expectations of technology relevance and usefulness, and it is influenced by prior experience. Concerns about data management (e.g., governance, quality, privacy, security) take a back seat to more practical issues such as profitability, leaving producers in an imbalanced position with tech companies who have an interest in their agricultural data. We assert that producer acceptance of data management practices (despite their uncertainty in how to utilize the data being generated) implies that there is a basic level of trust in tech companies' data management practices that is consistent with models of moralistic trust behaviors for precision ag adoption. Our findings contribute to the growing research on digital agriculture that debates the benefits and downsides of digital agriculture.

KEYWORDS

Internet of Things (IoT), technology adoption, UTAUT-2, TAM3, agricultural technology

1 Introduction

Digital agriculture enabled by the Internet of Things (IoT) is transformative technology that empowers farmers to make data-informed decisions to optimize resource allocation, reduce waste, and enhance productivity. IoT technology refers to networks of sensors and digital devices that autonomously connect and share data, with minimal human prompting (Farooq et al., 2019; Kagan et al., 2022; Liu et al., 2021). As shown in Figure 1, IoT technologies include sensors, robotics, and unmanned aircraft that interface to detect water and nutrient content in row or orchard crops. Sensors attached to plants transmit data that is collected by unmanned aircraft and transmitted through communications networks, typically in rural areas. The development of these systems involves multiple points for data management which warrants closer examination whether agricultural producers are willing to give up management

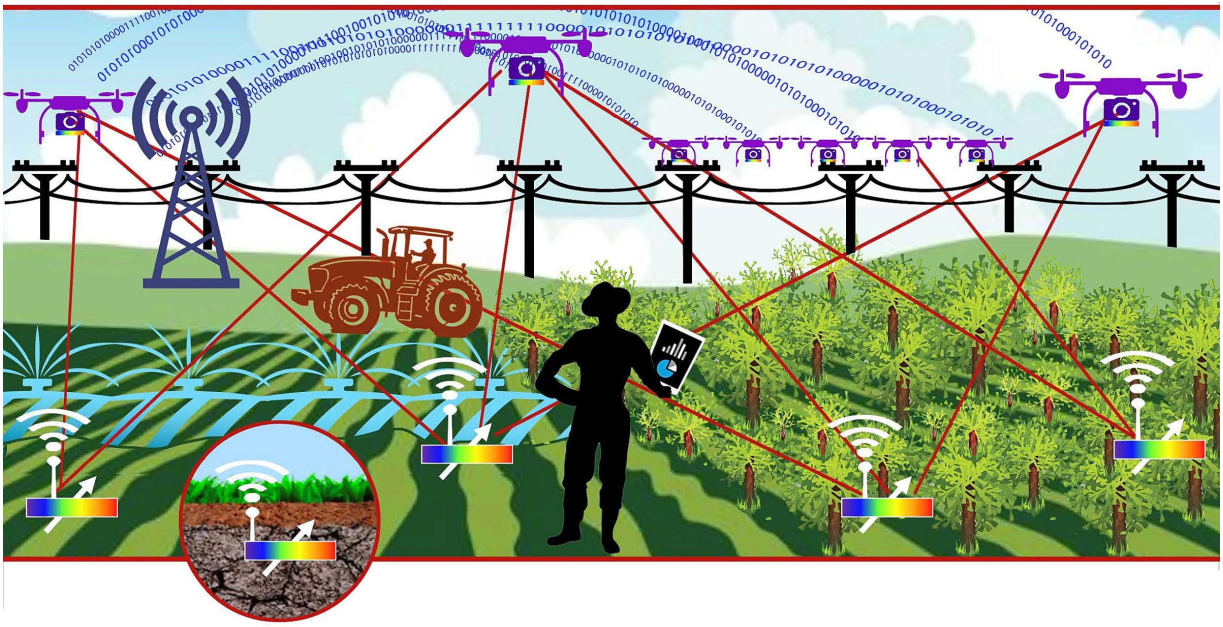

FIGURE 1
Internet of Things (IoT) agricultural system with sensors, robotics, and unmanned aircraft transmitting data viewable by a farmer on a tablet. Reprinted with permission from the IoT4Ag Gen-4 NSF ERC (https://iot4ag.us) © IoT4Ag ERC.

of data in exchange for improved nutrient detection that provides the potential for improved profitability.

IoT technologies involve ubiquitous sensing, autonomous farming, and big data. These are extensions of digital agriculture, which utilizes tools that collect and analyze data from agricultural applications that may extend beyond the farmgate and throughout the entire agricultural value chain (Shepherd et al., 2018). Digital agriculture encompasses precision agriculture technology that enables farmers to modify input (e.g., water and nitrogen) applications (Osrof et al., 2023). In other examples of digital agriculture, Agribots, for example, have taken to seed mapping, weed mapping, and micro spraying throughout various countries (Revise as Reddy, 2016).

Despite its potential benefits, the adoption of digital agriculture is uneven (Osrof et al., 2023). Larger farms are most likely to realize economic benefits of automation through reduced labor costs and can spread the fixed costs of technology investment across a larger acreage (Basso and Antle, 2020). The economic advantage provided by digital agriculture may thereby result in large farms becoming larger and farm consolidation, a phenomenon that has been documented in the 2022 Census of Agriculture (USDA, 2024).

Data managed as a commodity is of interest to companies throughout the supply chain. Some farmers have begun to view data as an asset to be managed like other farm assets (Wiseman and Sanderson, 2019; Wysel et al., 2021) that can be shared or sold. As more technology solutions are developed and deployed in agriculture, farming dynamics continue to change, often placing farmers in a subordinate relationship to technology companies (Neubauer, 2021). Some studies have indicated that farmers using ag data software products and sharing data with outside consultants are significantly more likely to make data-informed management decisions, with these farmers also more likely to regard their decisions as yield-enhancing (DeLay et al., 2020). However, other authors (Gardezi and Stock, 2021) have expressed concern that farmers are adopting digital agriculture to be morally complicit, in other words to be viewed as "good farmers" that contribute to food security; meanwhile, agtech firms have successfully positioned their knowledge products as superior to farmers' experiential knowledge, thereby perpetuating farmers' sustained engagement with digital agriculture technologies for the purposes of data capture and corporate capital accumulation.

Without understanding barriers to adopting digital agriculture technology, there is strong potential to perpetuate imbalances between farmers and tech companies, and between large and small farmers, as digital agriculture and IoT technology expand (Soma and Nuckchady, 2021). Faik et al. (2024) note that poverty limits the affordability of digital technologies for segments of the population, and that small farming operations may have insufficient means to acquire digital technology. Furthermore, there is great importance to engage small farmers in technology adoption, due to the high prevalence of small farmers. According to Lowder et al. (2021), farms of less than two hectares comprise 84% of all farms, though they operate 12% of all agricultural land.

We contribute to the literature by assessing user adoption behavior and barriers to digital agriculture technology through 21 qualitative interviews with medium sized almond growers and technology consultants in California's Central Valley, and by identifying potential strategies to increase adoption. Utilizing abductive reasoning (Dubois and Gadde, 2002, 2014) to cycle between theory and our data, we infer the best explanation for this reluctance to adopt new technologies. Through this iterative analysis of our interview data, we apply the Technology Acceptance Model (TAM-3) (Venkatesh and Bala, 2008) and the Unified Theory of Acceptance and Use of Technology (UTAUT-2) (Venkatesh et al., 2012) to frame our findings. Our results indicate that economic profitability is the foremost factor influencing producers' decisions to adopt technology. Trust in technology performance, and in those who recommend it, is a moderating factor that either facilitates or hinders adoption. de Vries et al. (2023) identified a need for nuanced exploration of how trust influences the adoption of digital technologies in the agri-food value chain, and identified three themes. Our work contributes to the theme 'trust and digitalization,' largely through the lens of production-focused technologies. Interestingly, concerns about data management logistics are secondary to profitability, aligning with Gardezi and Stock's (2021) notion of moralistic trust in corporate entities, who are perceived as inherently trustworthy in their data management practices. However, this finding contrasts with the work of other authors (Fielke et al., 2022; Jakku et al., 2019; Wiseman et al., 2019).

Next, we provide a literature review on the TAM-3 and UTAUT-2 models and the literature on digital data management practices. This is followed by a description of the methodology, discussion, and conclusions.

2 Literature review

TAM-3 and UTAUT-2 are based upon the widely accepted Technology Acceptance Model (TAM) for examining barriers to adopting computers, first introduced by Davis (1989), which is an adaptation of Ajzen's (1991) Theory of Planned Behavior that behavior follows intention. Davis's TAM found that perceived usefulness (PU) and perceived ease of use (PEOU) were both critical to technology adoption. The TAM has been used in other agricultural tech adoption studies to examine the willingness to adopt a nutrient management plan in Ireland (McCormack et al., 2021), precision agriculture adoption in Canada (Aubert et al., 2012), technology adoption in Indian agricultural industries (Kumari et al., 2018), unmanned aerial vehicles in Turkey (Parmaksiz and Cinar, 2023), agricultural e-commerce in Iran (Zarei et al., 2022) and larger technology systems or bundles such as integrated pest control and smart farming (Rezaei et al., 2020; Silva et al., 2017; Tubtiang and Pipatpanuvittaya, 2015). However, though there is no evidence of the use of TAM to evaluate barriers to adopting digital agriculture technology in the United States, it is often used to explain adoption and use of technology service bundles in general (Schilke and Wirtz, 2012). The TAM-3 and UTAUT-2 models advance the TAM model by incorporating new variables and by considering evolving technology and user behaviors like perceived enjoyment, social influence (from peers, social networks, and social media), and external variables such as trust, subjective norms, and facilitating conditions. The UTAUT-2 introduces several new constructs such as performance expectancy, effort expectancy, social influence, and facilitating conditions. These factors help in understanding the influence of external factors, social norms, and perceived usefulness on technology adoption. The UTAUT-2 also considers moderating variables like gender, age, experience, and voluntary use, which can influence the relationship between the determinants and actual technology usage. The UTAUT-2 also acknowledges the importance of context in technology adoption, considering organizational, cultural, and situational factors.

Shi et al. (2022) use the UTAUT-2 model to examine the contributing factors that make Bangladesh farmers willing to pay for and to adopt IoT. They find that a government developed IoT infrastructure, and subsidies are critical facilitating conditions to promulgate adoption and for creating an affordable system that will ensure commodity price competitiveness.

Using the TAM-3 and UTAUT-2 frameworks, we identify new themes to consider for targeted intervention and strategies to promote the adoption of digital agriculture and how the chasm between early adoption and late adoption can be bridged. Late adopters often cannot access new services or processes (Woodcock, 2014), which in the case of small farmers will leave them further economically disadvantaged, possibly leading to a downward spiral of being unable to catch up with technology adopters and large farms, becoming further marginalized and non-competitive. Not surprisingly, our study finds that the adoption of technology is highly dependent on whether it increases farm profitability. However, unlike earlier findings on trust in digital technology companies (e.g., Fielke et al., 2022; Jakku et al., 2019; Wiseman et al., 2019), concerns about data sharing with these companies seem to be of lesser importance to our participants, leaving farmers in a vulnerable position regarding data management.

Digital agriculture has the potential to increase productivity in a transformative way, and hence, to improve profitability, while reducing environmental impact. Weersink et al. (2018) note that agricultural practices have been slow to change, and although there is greater data generated, the cost savings and improvements to profitability are demonstratable on a case-by-case basis:

> "But despite these obvious benefits, it must be noted that the value of the additional information provided from precision agriculture relative to its cost is another likely barrier hindering its widespread adoption. In particular, the history of how farmers use technologies such as yield monitors and variable application rate fertilizers suggests a relatively flat payoff function for these technologies that in many cases means there is no real financial incentive for farmers to invest. Hence, the existing evidence points to extremely varied uptake." (Weersink et al., 2018, p. 23)

In a survey of European farmers, Barnes et al. (2019) found that high costs of purchase, along with small farm size are the top two reasons for non-adoption of precision ag technology. Lack of information, low return on investment, and farmer age rounded out the top reasons for non-adoption. Similarly, the authors found that decreased production costs were the top reason for adopting technology.

Lowenberg-DeBoer and Erickson (2019) note that some aspects of precision agriculture technologies like Global Navigation Satellite Systems have been adopted rapidly, while other technologies, such as variable rate technology (VRT) application have proven to be slower to being adopted, due to uncertainties in achieving financial payback. DeLay et al. (2022) found that profitability and technical efficiency both increase with technology bundling of complementary products. Bundling examples include yield monitors and grid soil sampling; and, aerial imagery, hand-held GPS devices, and soil survey maps.

In a copious literature review of digital agriculture from a social science lens, Klerkx et al. (2019) indicate a need to prioritize tech adoption research on data ownership, privacy and ethics in digitalizing agricultural production systems. As van der Burg et al. (2021) point out, there are several studies, implemented through surveys and interviews, that indicate farmers are hesitant to share their data through lack of trust. Among these, Wiseman et al. (2019) surveyed 1,000 agricultural operations in Australia, finding that a lack of understanding about how data will be used is among farmers' chief hesitancies about sharing data, despite the widespread adoption of digital technology in animal agriculture contexts, like dairy milking stations. Wiseman et al. (2019) also indicate that farmers are uncomfortable with the sale of data extracted from digital ag technology for profit. In interviews with 26 grain farmers and agricultural industry stakeholders, Jakku et al. (2019) note that trust over how data will be used is a central concern, which creates skepticism of the value of digital technologies.

Trust has been cited as a key factor in technology adoption (McKnight et al., 2002, 2011; McKnight and Chervany, 2006). TAM and UTAUT, while useful models, do not capture the role of trust in predicting adoption behaviors (Gefen et al., 2003; McKnight et al., 2002). Strategic trust is characterized by beliefs in the trustworthiness of technology (or people) and beliefs based on experience (Gardezi and Stock, 2021). The traditional strategic trust concepts – general trust, context trust, and specific trust – apply equally to technologies as they do for personal and institutional trust environments (McKnight et al., 2002). Where technology is concerned, general trust reflects an individual's personal propensity to trust technology. Context trust is tied to expectations of relevance or usefulness of a class of technology, and specific trust is anchored in experience with a specific technology (McKnight et al., 2011). Early adopters typically have high levels of general trust while late adopters and laggards come with low levels of general trust, leading to greater reliance on expectations and experience to build other forms of strategic trust.

Moralistic trust, unlike strategic trust, does not rely on rational assessment. Rather, it is rooted in a societal or community culture (Gardezi and Stock, 2021). To be perceived as responsible members of their community, farmers may choose to adopt tools and techniques used by their peers, trusting that all involved parties (vendors, government, customers, etc.) are collectively working for the common good. For instance, digital agriculture technologies have been used to enhance consumer-grower trust by allowing growers to provide more transparency and traceability in their operations, signaling good farming practices to their customers (Finlay-Smits et al., 2023).

Our study finds that farmers prioritize expected gains in profitability as the leading motivation for adopting digital agriculture. Trust in technology and in those who recommend it serves as a moderating factor to whether digital technology will be adopted. Our study is also the first to frame digital ag adoption with almond growers. Most technology studies have been conducted with row crops, though a handful of studies have been implemented with apple orchards and the olive sector. Gallardo and Sauer (2018) examined technology adoption to address the need for labor saving technologies in agriculture with apple orchards. Gallardo and Brady (2015) looked at barriers to adopting platforms during harvesting, in lieu of ladders, that would improve farm worker safety and labor productivity in apple orchards. In contrast to Gallardo and Brady (2015), our study focuses on digital technology, rather than mechanization. Parra-López et al. (2024) implemented a semi-quantitative multicriteria framework to assess the impact that technological innovation systems have in facilitating digital transformation in the olive sector in Andalusia, Spain. The authors note that, "As data becomes a valuable asset in agriculture, safeguarding the rights of all stakeholders to their data ensures not only ethical practice, but also trust in the digital transition." (p. 12). Our results are consistent with the findings of Parra-López et al. (2024). Next, we discuss study methodology, findings, discussion, and conclusions.

3 Methodology

Our investigation was approved by the University of California Merced Institutional Review Board (Study # UCM 2021-115). We developed a semi-structured interview protocol to evaluate six main topics: cost, technological compatibility, IT Infrastructure, data management, data privacy, and cybersecurity with an average of three questions per topic.

Using cognitive framing as our analytical lens, our interview questions probed experiences with agriculture technology adoption. We included prompts related to data management given that prior studies have indicated data privacy may be an issue for growers (Jakku et al., 2019; Wiseman et al., 2019). We developed 3 background questions at the beginning and three closing questions at the end of interviews to ensure participants had the opportunity to share any experiences during our conversation.

Three focus groups with eight participants were conducted to validate and test the protocol. Employing snowball sampling (Parker et al., 2019), from January through August 2022, we conducted semi-structured interviews with eleven almond producers from small and mid-sized family farms[1] and ten industry professionals representing a mix of ag technology companies and farm advisors, all of whom had experience assisting producers with the implementation of digital ag technology. All subjects were from Central California.

Our audio recorded interviews each lasted approximately one hour and were later transcribed. During the interviews, we focused on listening to what growers said about barriers with no pre-conceived framework for analysis, consistent with grounded theory methodology (Glaser and Strauss, 2017).

Applying abductive reasoning (Dubois and Gadde, 2002, 2014) to the generally held observation that there is low adoption of new technology in agriculture, we use our interview data to infer the best explanation for this reluctance. After familiarizing ourselves with the data, we determined that a framework based on TAM would be appropriate, leading to the development of our initial NVivo codebook based on TAM-3. While TAM-2 and TAM-3 are both extensions of the original TAM model, we selected TAM-3 because it can be used to identify adoption barriers as well as potential interventions (Venkatesh and Bala, 2008). Interviews were coded in NVivo software by the lead author and research assistant, who collaboratively drafted a coding scheme that was inclusive of initial insights and reconciled their results for internal consistency and reproducibility. Each coder separately coded the same five interviews, then discussed, revised, and added code themes, as appropriate. For the rest of the interviews, the research assistant coded the remaining

1 We use the Economic Research Service farm typology (Hoppe and MacDonald, 2013) to define small and mid-sized family farms. This typology considers the ownership structure (owned by family) and gross cash farming income (GCFI) to further classify small (low and moderate sales), medium, and large family farms. The farms represented in our sample span the small and medium GCFI categories ranges.

interviews with the lead author suggesting changes to codes and coding. After this first round of coding, the lead author undertook repeated rounds of coding, categorizing, and comparing. In addition, both authors discussed the coded interview quotes to further refine code definitions and identify core themes —a process that led to the inclusion of price value from UTAUT-2 and the development of a more holistic, hierarchical framework for interpreting our results. Through this iterative process, *trust* emerged as an important factor in the adoption decision.

We now describe the in-depth qualitative insights that we theorized to develop our conceptual model. The letter-number pairs at the end of each interview quotes indicated the interviewee who made those comments, with G indicating a grower and C indicating a consultant; select demographic characteristics of the interviewees are found in Table 1.

4 Results

In our initial analysis, we identified a conceptual model that identified expectations, experience, and, most importantly, economics, as the factors influencing adoption decisions, just as earlier research would have us expect. However, while no one research subject specifically mentioned it, trust emerged as a construct worth deeper investigation. After another pass at the data, coding for trust, we saw evidence that trust could moderate the relationship between rational economic arguments to adopt and adoption – if a grower does not trust that a new technology will perform as promised, then they will be less willing to invest in that technology.

We engaged in an exploratory correlation cluster analysis using NVivo's built-in functionality. As coding data are binary, we used the Jaccard coefficient to examine the relationship between codes. We found that a stable core of five clusters emerged, as presented in Figure 2A. When combined with our initial conceptual model, we interpreted the clusters with the lens of our initial conceptual model (Figure 2B). Using this interpretation, we refined our conceptual model, providing nuance to the important expectations, experiences, and economic factors that guide adoption decisions, as presented in Figure 3. Below we discuss these constructs with quotes from our data.

Economics, *expectations*, and *experience* form the foundational concerns when making a new technology adoption decision. Expectations are set, which are then influenced by past experiences both directly and indirectly with agricultural technology implementations. Our conceptual model (Figure 3) depicts how these types of frames – economics, expectations, and experiences shape the adoption of new agriculture technology in tree crops. An important element that emerged from the data is the role of trust in adoption. We found comments in many interviews that speak to how much trust growers have, or can have, that the technology will deliver the promised value. We interpret trust as a moderator, facilitating or hindering the effect of economic arguments to adopt.

The model presented in Figure 3 shows the interactions between core concepts. However, the relationships between these concepts are

TABLE 1 Interviewee demographics.

Age group	Growers	Consultants
20–29	3	0
30–39	0	3
40–49	4	4
50–59	0	1
60+	4	2

To protect participant anonymity, gender and race are not explicitly indicated. Among the 21 interviewees, 15 self-identified as white, while the remaining six identified as American Indian/Alaska Native, Asian, or Portuguese-American. One grower identified as a woman.

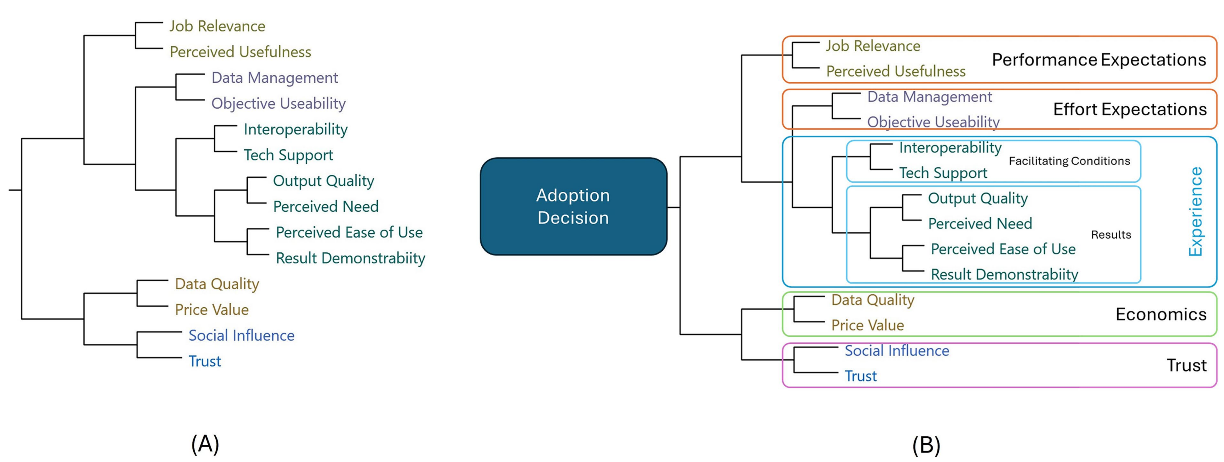

FIGURE 2
Code clusters determined by NVivo using Jaccard coefficient **(A)**, and interpreted through the lens of our initial conceptual model **(B)**.

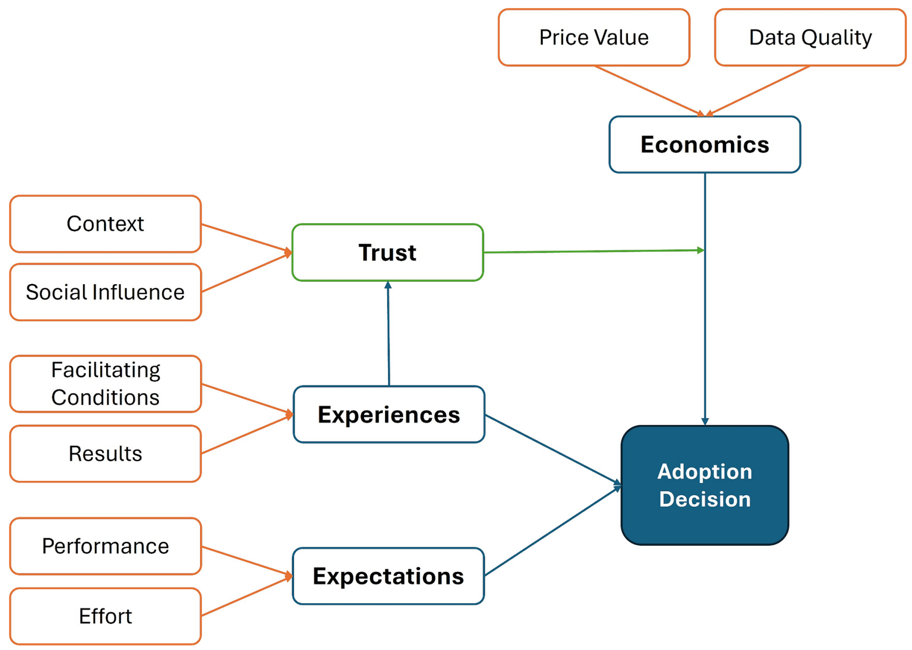

FIGURE 3
Conceptual model of ag tech adoption decision.

TABLE 2 Issue framing on economics construct.

	Issue	Exemplar quote
Price value	Open to adopt when value demonstrated.	*And I would say we are a company that does not shy away from it just because the price of it, if it makes sense, it's going to bring value.* (G5)
	Investments are assessed against size of the farm.	*I would love a self-driving sprayer, all that kind of stuff. But there's no way that could be financially justifiable for the size of my operation so economically I cannot do it. So, a lot of that stuff is like, yeah You want it, but you cannot afford it and there's no way.* (G1)
	Subscription models can have advantages, especially for smaller operations.	*You know, having a company own and operate the equipment, right? Yeah, it's much better for a company to come offer a service* versus *offer a product like do not offer a weather station, offer me weather station service, right?* (G9)
Data quality	Improving decision making is an important benefit of agtech and requires quality data.	*You know, and that's my goal in every tool I can find. Make it more precise, in other words. 'Should I wait until June 1st to start water?' […] Anything that can help me make that decision, when to put the water and how much – so I'm not running water past the red zone, every drop is getting used – that's a big value to any grower.* (G3)
	Timely data have greater value.	*I'd rather have information literally any hour I want it* versus *one hour on another guy's time once a week.* (G6)

dynamic. As growers gain experience with technology, they update both expectations and trust.

As discussed in the literature review and elsewhere (Marra et al., 2003), if the economic value of a technology is there, then growers are interested in adopting it. However, the economics of a technology have a heavy dependence on the size of the farming operation and the pricing model (subscription/lease versus ownership). Data quality directly impacts assessments of the economic value as well, although other data management concerns (e.g., governance, security, and privacy) do not appear to be directly linked to the economic dimension in technology adoption; rather, these aspects of data management appear to be more closely associated with effort and experience assessments (see Table 2).

4.1 Functionality

Broadly speaking, two groups of factors influence the beliefs about the functionality of a new technology: performance and effort *expectations*, and direct and indirect *experiences* with the technology.

> […] every technology that has succeeded on this farm has made someone's life easier, right? And more importantly, the active user right to his point, right. The ones I've tried to do that don't work, make it say better for me, but harder on the employees, right? And it's more work for them and those just never seem to stick. (G9)

4.1.1 Expectations

When considering new technology, its expected performance – its relevance and usefulness in addressing the problem – is critical; the economic argument cannot begin to be made until there is evidence that the technology will work for the operation. However, we often saw complaints about the relevance or usefulness of data that are provided by sensor systems.

When performance expectations are positive, the effort expected to achieve them is assessed.

> Well. We try not to, we try not to invest in things that we think there's that steep learning curve (G10)

The effort required to understand the data is as critical to adoption decisions as the effort expended in collecting it. It's not surprising to hear that if the data cannot be easily used to support decision making, then it is of little value to farmers. High quality data at low effort makes the economic argument for adoption stronger (see Table 3).

> Our data demonstrate that data management and the objective useability are primary dimensions of effort considered by our participants. Our participants' current approaches to data management center around Excel (spreadsheets) and paper documents for farm management and decision making. a spreadsheet is probably as good as it gets. If you can, we will, we, we will help them put in this Excel spreadsheet. (C5) we track like yields and stuff like that … Just [in] Excel, on paper that type of stuff very basic just to get. Yeah. So Excel is a big one. (G4)

Issues with data input through other tools (e.g., integrating with an accounting system, gathering data for a [new] tool), increase the effort and decrease useability. It's unsurprising that where farmers expect adoption to require high effort, they are less likely to move forward with adoption.

4.1.2 Experience

Experience breaks into two clusters—facilitating conditions and results. Facilitating conditions are situations that need to be in place to support successful implementation of a new technology.

> I think there's not a problem in adopting precision ag as long as it's been proven to actually, yeah, well, I guess the problem is, can it be proven to make people money? (C9)

Past experiences with lack of interoperability and poor access to tech support have negatively affected farmers—without these critical facilitating conditions, the risks posed by a new technology are often assessed as too high. Tech support takes many forms – setting up new systems, updating hardware and software, facilitating self-repair options, and, critically, fast response to replace or repair equipment especially during critical growing operations. Given the remote settings for equipment deployment, response time is always an issue if something malfunctions in the field (see Table 4).

When it comes to results, past experiences—such as beta testing, personal adoption, or observing others' adoption—play a key role in evaluating new technologies. These technologies are assessed based on the quality of output, necessity, ease of use, and demonstration of results, particularly regarding how well they have supported improved decisions or operational outcomes on the farm. This evaluation also includes comparing the performance of existing systems and technologies already in place to address the business problem (see Table 5).

4.2 Trust

McKnight et al. (2002) argue that trust is an essential element in adoption, and that the traditional strategic trust concepts – general trust, context trust, and specific trust – apply equally to technologies as they do for personal and institutional trust environments. Strategic trust is characterized by beliefs in the trustworthiness of technology (or people), and beliefs based on experience (Gardezi and Stock, 2021). We find evidence supporting the need for strategic trust in both people and technology.

> …consistent, repeatable success is a big thing… (G4)

General trust in technology is characterized as a willingness to depend on it across a spectrum of situations, the assumption that technology is usually consistent, reliable, and functional, and that it

TABLE 3 Issue framing on expectancy construct.

	Issue	Exemplar quote
Performance	Too much information is not helpful.	*[Product] in particular, give [sic] me way too much information, and it's not relevant.* (G11)
	Must be able to act on the information provided.	*So if you tell me that this area is dry and this area is wet, there is not anything else I can do about it. It just does not work. Or this area is low on nitrogen and this area is high. Nothing I can do about it because we fertigate, we run our fertilizer through the irrigation system. So telling you those things is not that useful.* (G11)
Effort	Systems that can reduce the effort of collecting quality data are appreciated.	*We do not have necessarily time to be checking these traps and deals […] But any of that technology, they can give us real time data that we can analyze. It's, it's huge.* (G5)
	Adding steps or new processes increases resistance.	*And you also, everyday have to go and hook up your laptop to this soil moisture probe and download all the data. It's like, Wow, why do not I just go out there with a hand probe?* (C4)
	Frequent changes are a burden.	*[…] for these things to be successful, there has to be inherent simplicity and, and a continuum in them. You know, constantly tinkering with them becomes a…just a giant nuisance to farmers because they do not have time to relearn it.* (C8)

TABLE 4 Issue framing on experience with facilitating conditions construct.

	Issue	Exemplar quote
Facilitating Conditions	Incompatible systems create work, increase risk of obsolescence.	*You know, I mean, to this point, every technology I've ever subscribed to or bought, and none of it talks to each other. Right? It's all just whatever it is that you are getting right. There's nothing that like, you know, that talks to each other, right?* (G9)
	Value of new systems reduced if cannot integrate with existing (widely-adopted) products.	*There was an ag business software that, you know, you could write your recommendations in and keep track of your product cost in and stuff like that but it wasn't compatible with [Product]. You know where [Product] is like the industry standard of recommendation writing and the store house of all the labels of the different insecticides and fungicides and herbicides that are out there. It's like if you are going to have some sort of tool like that it needs to be able to talk to [Product], otherwise what are you doing?* (G1)
	Interoperability adds value: better decisions at lower effort.	*[Product A] one of the greatest things they did is they linked their, their, their [Product A] app with [Product B]. So you could plan your irrigation as well as plan your field events. All at the same time.* (C2)
	Uncertainty about maintenance and support availability increase friction.	*And so like the factors would be like. If we are, if we, if we encounter breakdown difficulties, parts availability service, you know, is this, is this, is this system actually tried and true?* (G10) *But what happens if they start breaking? What happens? Problems start happening. You have to call someone out. You have to wait. That's killing your time.* (G4) *There's a lot of instruments that work, but they have to be serviced. And as a farmer, we only have so much time to supervise and manage our business* (G3)
	Quality of support experiences affect general trust in new products.	*If they go and buy $20,000 of equipment and then a month later, it's not working and no one's there to help them. So it's like that constant. That's why it takes a long time to, like, introduce stuff into the industry because it takes time to build that base of reliable technology.* (G4)

TABLE 5 Issue framing on experience with results construct.

	Issue	Exemplar quote
Results	Meeting a perceived need drives adoption interest.	*I think the most, most important thing, at least in regards to almonds and walnuts, would be a yield harvest monitor, right? If there is a way. That's essentially what has…a yield harvest monitor is what's allowed the Midwest to become what they become with technology. You know, because none of this data makes any sense, really, until you can overlay it with a yield map […]* (G9)
	Where no need is identified, technology is a hard sell.	*Or they just think, 'oh, technology, we do not need it. We've been doing this for generations, so we are doing fine', you know?* (G7)
	Early adopters risk poor results.	*But still, we need productivity, right? And sometimes some of the newer technology we do not want to see, we struggle. The technology struggles, which affects our productivity, …* (G5)

provides better outcomes when it does meet these assumptions (McKnight et al., 2002). This general disposition to trust is considered an individual characteristic and, while we may be able to infer some participants' general trusting beliefs from their comments, we did not directly examine this in our conversations. However, consultants seemed to indicate that growers do not have very high levels of general trust in technology. For emerging technology, promises have been broken in the past – results did not match expectations or companies disappeared – so there is greater proof needed to overcome low levels of general trust (see Table 6).

Unlike general trust, context and specific trust are rooted in expectations and experience with focal technologies. Context trust reflects the expectations of relevance and usefulness of a class of technology – for example, that irrigation technology provides a useful solution to a relevant challenge faced by growers. Our interviews uncovered many examples of technologies evaluated as having job relevance and reliable results; in these cases, there were favorable adoption attitudes.

On the other hand, we also found cases where the growers felt the results did not live up to the industry hype; instead, they could do as well with existing, established practices.

> We already bought the weeder and [Partner] went to Italy and we got we sold it already. There you go. And it made so much sense, right? [Partner] went to Italy. You got to get the planter to match up with the weeder, so you get the auto planner and then you're going to get the weeder and everything's going to marry up and we're going to save a ton of money and labor's hard to find, you know, so let's do it and we did it and the weeder couldn't weed. (G5)

Relationships are at the heart of building specific trust. Where a grower may trust irrigation technology, their trust in a *specific* irrigation solution will depend on experience with the product, its vendor, and even a specific salesperson. Further, this type of trust can be influenced by other trusted sources of information – peers and extension agents, for example.

> Our sales are because of neighbors talking to other neighbors, to other farmers, and letting they know "hey if you got a, a problem call these guys. They work weekends, they work nights, and they will get you going," because farming, when it's go time, it's go time. There is no stopping. (C10)

TABLE 6 Issue framing in the formation of strategic and moralistic trust.

Disposition to trust		
	Early adopters show higher levels of general trust in technology.	*I would be willing to be the first. Me personally, I'm, I'm, I'm cool being an early adopter and spending some extra cash.* (G8)
Strategic trust		
General technology	There have been too many bad experiences with ag tech in the past. (general trust in technology)	*'Hey, this thing is going to do your taxes, it's going to mow your field, and it's going to tell you you are showing moisture and give you the moon.' And then it does not do that. And then they, and then they have a second guy come in. They're like, 'OK, I'm going to trust you. I'm going to try to trust you.' Same thing happens again, and then they are burned on all technology. They say all technology is the same, does not work.* (C3)
Contextual	Certain types of organizations are less trusted given the way they have approached agtech historically.	*I feel like Silicon Valley has actually hurt precision agriculture adoption, because you had a lot of guys […] came from a true blue Silicon Valley startup that saw agriculture and was like, 'Oh, sweet, there's this cash cow that nobody knows about.' […] and very quickly we found out […] we are actually behind the curve. […] And so then they start pushing and they start pushing the development process too quickly. So then they put something out that's unreliable.* (C3)
Specific	The word of a trusted advisor or peer can overcome uncertainty.	*[…] they do not know the value. And so they just kind of, I have to trust someone.* (C7)
	Relationships can form chains of trust.	*The grower does not know me, grower does not know [Company], grower knows [Salesperson]. "[Salesperson]'s my guy when I need something. [Salesperson] takes care of it for me. [Salesperson]'s going to a different company. Do they sell everything I need? Can you make it happen?" […] So [Salesperson] 's not going to jeopardize his connection with me, and then the grower is not going to talk to me directly either.* (C1)
	Some products have proven themselves.	*But if I did not have those meters or did not have confidence in those meters to not know how much of my 28 inches I'd used, yeah, because [Product] wasn't available it would be very frustrating because whatever I go over, it's going to cost one hundred and fifty dollars an acre foot.* (G11)
Moralistic trust		
Social influence	Seeing your peers using a product builds confidence.	*Knowing that, eh, local farmer has bought the product also.* (C10)
	Respect for and reliance on experienced peers.	*Sometimes you ask them, 'hey, why do you do that?' 'Oh, my neighbor started it. All right. I do not know. But he's a good grower, so I'll copy him.'* (C9)

Moralistic trust, unlike strategic trust, does not rely on rational assessment, but rather is rooted in a societal or community culture (Gardezi and Stock, 2021). Social influence is described as "…the extent to which consumers perceive that important others believe they should use a particular technology" (Venkatesh et al., 2012, p. 159). This influence can be critical in forming generalized moralistic trust. To be perceived as responsible members of their community, farmers may choose to adopt tools and techniques used by their peers, trusting that all involved parties (vendors, government, customers, etc.) are collectively working for the common good. For example, in California, being seen as a good water steward is socially important. This social pressure can strongly motivate growers to adopt irrigation technologies, even if they have concerns about data management (e.g., privacy, sovereignty) or the reliability of a specific product.

> So whether it's, you know, our employees or our equipment or all the above, we, you know, our fertility and we, our water usage, we all, are under a microscope right to be able to do the right thing. And sustainability is doing the right thing so we can continue to pass it on to the next generation and continue to be profitable and all the things we've done. (G5)

This aspect of moralistic trust, where the adoption of technology is seen as an ethical commitment to sustainable practices, was particularly evident in discussions around the use of irrigation technology, which has seen widespread adoption among the growers in our sample.

> Determining how to use our water and the most efficient way is becoming a real big, big issue. Aerial imaging. Various methods of measuring soil moisture and interpreting what they mean. That's becoming more and more critical, we're, we're just short of water everywhere and in the West right now, but California particularly, so we're trying to learn how to farm with less water. (G3)

Moreover, when discussing the potential for chemical application technology, growers highlighted its value but also noted that current solutions are too costly for their operations. This contrast between the adoption of irrigation technology and the hesitation around chemical application technology further underscores the nuanced role that moralistic trust plays in technology adoption decisions.

> As far as like the GPS driven variable rate application type stuff. That stuff is not applicable to me because I have too small of blocks and it wouldn't make sense. Like it's too small. Why fertilize this area different than this area? It's, it's small like, put it all the same. You know what I mean? So, I couldn't justify getting a specialized piece of equipment that's gonna change the amount of fertilizer I put in one area of the field versus another one. (G1)

> They came up with a machine called GUSS and it was there at the Almond Conference, GUSS. It is a completely robotic self-driving sprayer, but they built this sprayer in a way that it covers like, they know exactly what it takes to spray an orchard, right? … So a thousand acre guy could probably buy one of these GUSS sprayers and justify more easily. (G1)

4.3 Data governance, privacy, and security

Not represented in our model (Figure 3) are worries about data management (e.g., governance, privacy, security). While these issues did arise, they took a back seat to the more practical concerns, leaving producers in an imbalanced position with tech companies.

> So again, with like the soil moisture sensors, I forgot to mention one part of the grant was that they would monitor how much water you're using per year for a year or two. So, the only issue with that that we talked about was if they use that data against us and say that we're using too much water. Which we're like, we're really not using that much water that is needed. Like, that's the part that we worry about. We really don't care if someone knows how much you're doing about. (G7)

The general sentiment was that the types of on-farm data collected would be of little value to competitors.

> No one's no one's going after [Product] because they know exactly what I know, which is nobody cares about your GPS maps. You know, there's no value in that to someone, you know, if they if they want to know, you know, anything of value, they want to know subscribers' private information. I guess email addresses might be valuable, but even then, like. (G10)
>
> This doesn't interest me! I'm not interested. Like you know do I like the fact of people taking the data and doing stuff with it? No. But is it a big decision-making thing for me? No, it doesn't drive my decision making. (G1)

Few growers seemed to have considered the question of data ownership. Among those who had given the issue some thought, they believed that the data belonged to them but assumed that the vendor would use the data solely to better serve their needs.

> And you think even if they [Product Vendor] owned that data, it would probably be working on your advantage […] I mean, realistically, it should be, you know, it should be my data, and it shouldn't be anybody else's unless I give permission for it to be used. Right? (G2)

5 Discussion

The barriers and challenges to adoption for our interviewees clearly align with standard findings of technology acceptance research, with the strongest indicators of early adoption lying in economics, expectations, and experience. Unfortunately, concerns in effort expectancy and facilitating conditions tend to outnumber the expected benefits of new technology which, when combined with low levels of experience with technology in our subject pool, largely explains low adoption rates even where a technology has proven performance benefits.

> So, I mean, I mean, we've been on the cutting edge of a lot of things over the years past and that cost you a lot of money, to be honest. (G5)

Perceived ease of use and impacts on profitability are among the most cited concerns for acceptance of digital technology. Since ag tech adoption is generally low among their peers, there is no pressure to adopt; social influence is more likely to reduce adoption behavior in our sample.

Early adopters showed signs they were willing to experiment, and they were comfortable with less refined solutions. In our sample, late adopters tended to be older farmers and there is evidence of some regret for waiting as they realized the lost opportunities.

> I never had a customer come back to me when they decided to move forward with, eh, [Product], and say I regret buying this. Every time is "why didn't I buy this five or ten years ago?" And the, their biggest regret is why didn't they do it sooner. (C10)

Unfortunately, in some cases it is the lack of supporting infrastructure that restricts the pace of adoption.

> [T] he RTK I mentioned, right, you need to connect to a cell network to be able to do that, in order to get your corrections, you might be in some area where there just isn't, you know, isn't into a lot of cell infrastructure or there are [sic] not very solid cell infrastructure. (C6)

Digital agriculture adoption among small-to medium-sized family growers is distinctly shaped by economics, particularly the challenge of large up-front investments required for advanced technology. Unlike large-scale growers with thousands of acres to allocate the investment across, small farms face significantly higher per-acre costs.

> …for me to get harvest equipment I would probably have to spend four hundred thousand dollars. For four hundred thousand dollars stretched across 55 acres is a very high dollar per acre amount right? Now if I had a thousand acres it makes sense to have your own harvest equipment because it's four hundred thousand dollars spread over a thousand acres instead of fifty-five. So the scale is very very important here. You're going to find that the smaller the farmer the more difficult it is to adopt the high tech kind of stuff. You know? (G1)

This challenge extends beyond operational functions to essential business support services such as accounting and billing, where it only becomes cost-effective to invest once the volume of transactions reaches a certain threshold.

> I'm sure if you're a big [grower] they farm 50,000 acres. I'm sure they have lots of technology in regards to accounting, right? For, for sending bills. I'm sure, you know, every guy's got a tablet and they have a budget and they have to. I know they log their time on their digital device right where we haven't gone there yet. We haven't needed to. We're probably going to get to that point if we're getting bigger, right? But you know, so there are certain thresholds in any size for certain technologies that fit. Yeah. (G9)

One strategy to mitigate this barrier is outsourcing, which allows small farms to access sophisticated technology without bearing the full cost. However, this approach has its limitations, as it may not always be possible to find service providers equipped with the latest technology, leaving these growers at a competitive disadvantage. Consequently, while outsourcing offers a partial solution, it often does not fully address the technology adoption disparity between small and large growers.

> I would love to be able to implement on my farm, like, lower dust technology for harvest. But again, I'm small right, and I'm hiring all this stuff out. And I don't know of any local service providers who have that type of technology, and if I did, I would consider having them come do mine. (G1)

Another advantage that enables large-scale growers to implement new technologies more quickly is their ability to hire full-time information technology staff to support users and manage systems.

> …it goes back to you asking about the IT guy on staff, something I feel like just maybe I live in a bubble. But from my experience, that type of deal only works on like a big scale operation. Because when you're working with like, say, two to like ten guys, all of those guys have tasks that need to do, and most of the time it's not [IT]. (G4)
>
> It matters how big you are. Oh yeah, I got my 10000 acre square is probably usually have a tech guy. On the 200 acre guys, probably not. Five acre guys definitely not. Yeah, I think it's, it's like any business like your scale if you can afford to or not. (C9)

In contrast, smaller growers must often operate without making new hires, placing additional pressure on existing workers to not only upskill but also to find the time to take on these extra responsibilities.

> …so yeah, me and my father-in-law are the IT team. (G6)

Considering these findings, it is important to reflect upon the transformations in social structure created by digital agriculture and how this potentially influences adoption behaviors. Some scholars have pointed out that reliance upon digitized systems has shifted traditional farming knowledge, which has in turn restructured farmer livelihoods and identities (Carolan, 2020). Early adopters may view using digital agriculture as being a part of a suite of good farming practices; they may accept digital agriculture as a standard operating procedure, whereas late adopters do not (Carolan, 2020). However, among all our participants there is an implied acknowledgement that data are routinely collected by agricultural tech companies. Our observation of the lack of immediate concern about data management suggests a privacy calculus (Dinev and Hart, 2006) where perceived privacy risk is low and is consistent with moralistic trust (Gardezi and Stock, 2021). We have evidence that growers do not consider their data to be of high value to an external attacker:

> …because they know exactly what I know, which is nobody cares about your GPS maps. You know, there's no value in that to someone (G10)

And little evidence that our participants have thought about how agtech companies could exploit aggregate farm data for profit at the expense of their client growers (i.e., the data subjects), although one grower noted:

> So, the only issue with that that we talked about was if they use that data against us and say that we're using too much water (G7)

Gardezi and Stock note that farmers are increasingly dependent upon the technology companies that collect their data, "… agricultural technology companies have successfully positioned their knowledge products as superior to farmers' experiential knowledge, thereby ensuring farmers' sustained engagement with [precision agriculture] technologies for the purposes of data capture and capital accumulation" (Gardezi and Stock, 2021, p. 1). Though this leaves agricultural producers in a vulnerable position with how their data are used, and ushers in concern about the fate of late adopters, the use of data by agricultural tech companies appears to be accepted as "fait accompli." Though some studies indicate that farmers may distrust agtech company use of their data (Fielke et al., 2022; Jakku et al., 2019; Wiseman et al., 2019), we interpret our finding of an absence of concern about data management as moralistic trust in the collection and use of data in digital agriculture. Producers internalize that data sharing is part of the digital agriculture process and a required aspect of the new way of farming, trusting their data will not be abused. The complex system of interdependent actors that makes up the modern agri-food value chain is poised for technology-enabled disruption, especially where data monetization opportunities exist. While growers may be comfortable for now and view the grower-agtech firm relationship as cooperative, we anticipate this position will change once they recognize the value of their data in the development of new agtech services and begin to manage data like any other business resource.

5.1 A way forward

Based on our analysis, we suggest a few approaches that target the economic, trust, and facilitating conditions concerns we heard in our interviews. First, addressing economic concerns, we suggest firms look closely at their business models. Leasing or service subscriptions seem more appealing (e.g., Precision ag as a Service, or PAaaS) for encouraging adoption, as they require less up-front investment. These PAaaS models can also address some of the support-related issues by including maintenance and troubleshooting as part of the subscription.

> That's where subscription service model, where it's OK, you get the subscription. We'll send a technician out every so often or someone on call to come out or, hey, we got this new technology we'll install it for the same price, whatever, and it is like, we can readjust the plan.

> Something like that might be more attractive to something like that, because then you're also getting the better technology. (G4)
>
> […] if somebody is paying for the subscription, I'm always there to pick up the phone for them. And that's where, you know, like I try to make that difference is, you know, understanding that these guys have been burned. I want to make sure that they feel that like they can feel secure. (C3)

However, this model requires that the technology demonstrates long-lasting benefits for the grower, or they will simply cancel the subscription once they have maximized the return.

> […] the farmer will use it for six months or seven months and love it. And then he'll pay the subscription for another two years and then finally just drop it and be like, I don't even use this anymore. You know? 'Cause a lot of the things are fixed after your six months of using that, whatever it is you're using, […] after six months where your inefficiencies are at. Right. But then for the next two years, you end up paying for it because you think you need it. But then it's like I already know. And it's, I've already cleaned it up and everything else you're showing me now is something I can't fix, you know? And so, then, they ended up getting dropped and it's not worth the subscription fee then. (C2)

Further, incentives do have a positive impact on adoption but can often be met with negativity. Mostly growers mentioned how some regulations are forcing them to adopt; a stick rather than a carrot that leaves a negative taste because typically the incentive is to meet reporting requirements to avoid fines.

> If I'm getting a benefit from the technology and helps me save this money, get this grant money I think it's a win-win. So that, so those incentives do help! You know? They really do. I do find those, sometimes they want to incentivize stuff but it's not the most practical of things. You know? With this one it happened to be very practical for me, but some of the stuff they are incentivizing are really unpractical. (G1)
>
> As soon as a new law or regulation comes out, there's a financial incentive to become more efficient to play within the boundaries and the rules of that regulation. You know, something like SGMA[2] right, is really made this irrigation thing. (G10)

The relationship between experience and trust is dynamic and agtech firms can leverage this dynamic to build trust and demonstrate the effectiveness of new technology by engaging in beta testing or low-cost demonstration implementations with early adopters. These activities not only showcase tangible results but also establish a base of users who can serve as peer support for new customers, thereby enhancing the facilitating condition of technical support. Additionally, trust is reinforced through social influence within the community.

> And so we partnered with a company [Company]. And so they've, they've kind of been working on different versions of doing that in different ways, and we've kind of given our ranch as a place to test that out. (G10)

Growers identify interoperability as a facilitating condition of adoption; there is a need to think in terms of systems and how new products interact with existing technology to provide information for decision-making. In essence, there's a need for general infrastructure support, for technologies that interoperate; systems are needed, not more siloed components. Increased interoperability and complementary systems increase yields and improve economic profitability (DeLay et al., 2022).

> … a yield harvest monitor is what's allowed the Midwest to become what they become with technology. You know, because none of this data makes any sense, really, until you can overlay it with a yield map … (G9)

Moreover, we concur with recommendations from other authors who have examined barriers to technology adoption in agricultural systems, and who have concluded that enhancing farmer trust is a lubricant for facilitating technology adoption. Eastwood et al. (2023) recommend using system approaches to design and develop technology, and to "… design and develop data governance, business models, and standards for data that are transparent, inspire trust, and share benefits of digital technologies among supply chain stakeholders" (p. 1). Fielke et al. (2022) note the benefits of redistributing trust between industry and farmers, and that "… providing institutional mechanisms to empower those actors that feel disempowered allows for progress in reducing antagonistic power relations and creating space for exploration of alternative arrangements" (p. 128). McGrath et al. (2023) point out the value of widening inclusion and farmer engagement in designing technology from the perspective of end-users. To summarize, we advocate for farmer engagement in product design, data governance, and innovation at all levels of the supply chain as a conduit to increasing trust, and thus technology adoption.

Our findings add to the literature on moralistic trust and expand upon the work of Gardezi and Stock (2021), although we contemplate whether there are regional influences from American subjects who may be more accepting of sharing farm data, compared to the Australian farmers in the Wiseman et al. (2019), Jakku et al. (2019), and Fielke et al. (2022) studies. Gardezi and Stock's work was conducted in South Dakota and Vermont (USA). Moreover, our subjects in California's Central Valley are within two hours of Silicon Valley, which is recognized as an international hub for technological innovation; hence, there is a possibility that familiarity with innovation creates a comfort level and acceptance of data sharing. In sum, we contribute to the literature that suggests that farmers aren't overly concerned about data privacy, though the potential for regionalism merits additional exploration.

6 Conclusion

In summary, our study shows that adoption of digital agriculture technology follows similar patterns with other

2 California's Sustainable Groundwater Management Act (SGMA) https://water.ca.gov/Programs/Groundwater-Management/SGMA-Groundwater-Management

industries, according to the TAM-3 and UTAUT-2 models. Our findings are also consistent with those of Gardezi and Stock (2021) promulgating that producers adopt precision agriculture as a feature of moralistic trust. However, given the importance of food production and the prevalence of small farmers, without making the value of tech adoption clear, small farmers may lag their peers and have difficulty catching up, which may further marginalize this population. To "bridge the disconnect between farmers and the tech community" (Nolet, 2018, p. 1) we must identify the value proposition of proposed digital agriculture solutions.

The benefits of engaging small farmers may pay off, in a way that advances digital technology to improve food security and minimize environmental impacts for all, write Dorin et al. (2022, p. 1): "Agricultural technology can potentially reduce poverty, increase well-being and food security, and drive economic development, but it has not yet, and it will not, unless changes are made in how it is created, applied and socially integrated".

Systems of agtech are needed to fully realize benefits of on-farm digitalization; siloed products cannot hope to address the complexities involved, and often do not improve economic profitability (DeLay et al., 2022). Development of whole systems requires collaboration and cooperation across the agtech industry, something that may need policy intervention to realize. Examples of needed cooperation include the development of standards so that smart devices such as sensors are interoperable or "platform agnostic".

To increase adoption, it is not enough to demonstrate theoretical economic benefits. The intelligent route forward is to first engage a broad set of stakeholders in identifying the most pressing needs. While growers are aware of potential economic benefits, their willingness to adopt new technologies often hinges on how well those technologies address their most significant challenges. It is critical to maintain this stakeholder engagement during development and testing phases and use partner-growers to demonstrate effectiveness. Such an approach not only ensures the most valuable systems are developed, but also builds strategic trust dimensions in both social and technology domains.

This work demonstrates the importance of profitability and trust in growers' adoption decisions and that data collection by agtech companies may not be the barrier for implementation of IoT technologies such as sensors. In future work, we will be looking more deeply at this interplay between profit, data, and trust through experiments to identify, for example, the willingness to pay for technology with select features. Our current work is limited in the small sample size of participants and the focus on organizational-level adoption decisions. Future work could explore the adoption by farm workers, including the impact of new technologies on the nature of their work.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by University of California Merced Institutional Review Board (Study # UCM 2021-115). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

MY: Conceptualization, Data curation, Formal analysis, Methodology, Project administration, Supervision, Visualization, Writing – original draft, Writing – review & editing, Software, Validation. CK: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Visualization, Writing – original draft, Writing – review & editing.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. This study was funded by the National Science Foundation NSF 19-503 Gen-4 Engineering Research Centers, award number (FAIN): EEC-1941529.

Acknowledgments

The authors extend appreciation to UC-Merced graduate students Alisha Nesslage, Christopher (Mikey) Bernal, and Nicolas Goncalves who assisted with data collection and analysis. The authors acknowledge the use of Chat-GPT 40 (https://chat.openai.com/) in light copy editing, for example, to improve the caption for Table 1. A supplemental document with all prompts and responses is available on request.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

Publisher's note

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TYPE Original Research
PUBLISHED 29 October 2024
DOI 10.3389/fsufs.2024.1452779

OPEN ACCESS

EDITED BY
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RECEIVED 21 June 2024
ACCEPTED 15 October 2024
PUBLISHED 29 October 2024

CITATION
Juventia SD and van Apeldoorn DF (2024) Strip cropping increases yield and revenue: multi-year analysis of an organic system in the Netherlands.
Front. Sustain. Food Syst. 8:1452779.
doi: 10.3389/fsufs.2024.1452779

Strip cropping increases yield and revenue: multi-year analysis of an organic system in the Netherlands

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Intercropping is proposed as a promising strategy to meet future food demand while reducing agriculture's environmental impact by re-diversifying agricultural fields. Strip cropping, a form of intercropping, has a potential to simultaneously deliver multiple ecosystem services including productivity, while facilitating management as strip width can be adjusted to the working width of available machines. While the yield performance of strip cropping systems is influenced by the interaction between neighboring crops, to date, empirical studies on the performance of various crop combinations in strip cropping systems are limited. Here we used three-year data (2020–2022) from a 64-ha organic strip cropping system in the Netherlands to (1) evaluate the effects of crop neighbors and strip cropping on yield and (2) explore if optimizing the allocation of crop neighbors in alternative strip cropping configurations can improve yield and revenue performances. We analyzed the edge effect and strip cropping effect on yield of six crops grown in strips, each neighboring a total of five crops. The yield data was then used to evaluate the performance of the current and alternative strip configurations in terms of LER and relative revenue. Results showed that except for the positive effect observed on potato when neighboring celeriac or broccoli, edge effects lacked statistical significance. Strip cropping effect varied per crop: positive for faba bean and parsnip, neutral for celeriac and potato, and negative for oat and onion. Analysis across crops showed an overall significant positive strip cropping effect on yield. These findings highlighted the value of analysis at the cropping system level in developing designs aimed at unlocking the potential of strip cropping. The positive but variable strip cropping effects observed in the current experimental design and the two alternative configurations suggests prioritizing an overall increased crop diversity over optimizing their spatial arrangement. While we demonstrated increased productivity with strip cropping, further research is needed to expand the database on optimal crop combinations, extending the evaluation beyond yield and revenue performances to facilitate broader adoption of strip cropping in the Netherlands and Western Europe.

KEYWORDS
intercropping, diversified cropping systems, crops combinations, land equivalent ratio, relative revenue

1 Introduction

Agricultural diversification has been put forward as a way to lower agriculture's environmental impact without penalizing its productivity (Tamburini et al., 2020), by reutilizing the agroecological functioning of agroecosystems that have been replaced by the intensive use of agrochemicals (IPES-Food, 2016). Among diversification practices, intercropping—the practice where multiple crops are grown simultaneously in the same field for at least part of their growing cycle—has been proposed as a promising strategy to simultaneously deliver multiple ecosystem services (Brooker et al., 2015; Beillouin et al., 2019a; Tamburini et al., 2020). In terms of yield, intercropping has been shown to increase yield quantity (see, e.g., Mu et al., 2013; Dong et al., 2018), quality (see, e.g., Bedoussac and Justes, 2010; Juventia et al., 2021), and stability (Stomph et al., 2019) compared to sole-crop monocultural systems. When implemented in organic systems, it has a potential to reduce the conventional-to-organic yield gap (Kremen and Miles, 2012; Ponisio et al., 2015).

In intercropping, crops can be arranged in different spatial arrangements, and the type and intensity of their interactions depend on the type of arrangement and species involved (Malézieux et al., 2009). In the Netherlands, dominated by intensive industrial agriculture, strip (inter-)cropping has received much attention (Schouten, 2018; Juventia et al., 2022). In strip cropping, long narrow strips consisting of multiple rows of one crop species are grown simultaneously next to strips of other crop species. Strips are wide enough to allow independent crop management by machinery but narrow enough for the crops to interact (Hauggaard-Nielsen, 2010; Juventia et al., 2021). The independent crop management strip cropping is considered easier to manage compared to other intercropping systems because the strip width can be adjusted to allow use of available farm equipment.

Several studies have shown the potential of strip cropping to deliver multiple ecosystem services. For instance, pest and disease control has been shown to be improved in strip cropping, compared to sole crop since the alternating strips of different crops can act as barriers in the field, thereby reducing the spread of pests and diseases (Bouws and Finckh, 2008; Ditzler et al., 2021b; Cuperus et al., 2023; Croijmans et al., 2024). Weed density was found to be significantly lower in strips compared to sole crops (Głowacka, 2013). Biodiversity is expected to increase as the spatial and temporal niche differentiation facilitates species to migrate to nearby strips during disturbance (Lopes et al., 2015; Hatt et al., 2017). Cultural ecosystem service in terms of aesthetic quality may be enhanced as the diversity within the field increases (Junge et al., 2015).

In addition to the above-mentioned ecosystem services, several studies have shown the potential of strip cropping to increase productivity compared to sole crop [see, e.g., Yu et al. (2015) and Zhu et al. (2023)], although the interactions between two crops that can benefit productivity in strip cropping are thought to mostly occur at the strip border, in the edge rows of the neighboring strips (Austin and Blackwell, 1980; Van Oort et al., 2020; Wang et al., 2020). This is in contrast to mixed intercropping where crops are sown together in no particular pattern or arrangement (Homulle et al., 2022). Facilitation and complementarity occurring through temporal, spatial, and chemical niche differentiation between the intercropped species are considered the main mechanisms to be responsible for increasing yield in intercropping systems (Justes et al., 2014; Duchene et al., 2017; Stomph et al., 2019). Temporal niche differentiation occurs when crops differ in crop growth and development patterns in time, leading to staggering in their concurrent nutrient and water requirements (Gebru, 2015; Dong et al., 2018). Spatial niche differentiation in leaf canopy or root system of the intercrops enables complementary use of available resources in terms of light interception as well as water and nutrient uptake from different canopy heights or different soil layers (Gebru, 2015). Intercrops may also have the ability to mobilize various chemical forms of nutrients, resulting in chemical differentiation (Homulle et al., 2022).

To minimize competition and promote complementarity or facilitation in strip cropping, the selection of crop combinations that would enable these mechanisms is essential. However, identifying crop combinations to optimize yield is a challenge given the currently limited empirical studies on the performance of different crop combinations in strip cropping systems (Isbell et al., 2017). Roughly 80% of meta-analyses on intercropping, species mixtures, and/or associated plant species focus on cereals and legumes (Beillouin et al., 2019b), with four legume species dominating 70% of the reviewed studies (Ditzler et al., 2021a). Given the growing need by current and aspiring farmers, advisors, and engaged researchers in the strip cropping network in the Netherlands, this paper aims to bridge the knowledge gap on what constitutes good crop combinations for optimizing yield. Furthermore, given that poor spatial configuration may lead to negative effects on the delivery of ecosystem services (Juventia et al., 2022), the potential of improving the production performance of the current crop rotation by optimizing the spatial allocation of crop neighbors will be explored.

To this end, we used three-year data (2020–2022) from a strip cropping system composed of eight arable crops at a commercial organic farm in the Netherlands to evaluate the effects of crop neighbors and strip cropping on yield and explore if optimizing the allocation of crop neighbors in alternative strip cropping configurations can improve yield and revenue performances. This question is divided in three research questions: (i) What is the effect of crop neighbors on the yield of the edge row compared to the center row in the strip (i.e., edge effect)?; (ii) What is the effect of strip cropping on yield per crop and across crops compared to sole crop reference (i.e., strip cropping effect)?; and (iii) What is the effect of the current and alternative strip cropping configurations compared to sole crop reference in terms of Land Equivalent Ratio (LER) and revenue? We hypothesized that the edge effect by the different crop neighbors would result in different yield performances and that the overall strip cropping effect would be neutral. We expected that an optimal configuration can be found by combining best performing combinations.

2 Materials and methods

2.1 Site description

The study was conducted from April 2020 to November 2022 on a 64-ha field of *Exploitatie Reservegronden Flevoland* (ERF B.V.) (52°23′33.1” N, 5°19′07.6″ E) representing an average farmsize in the Netherlands (BIN, 2023). ERF B.V. is the commercial part of a non-profit foundation *Beheer en Exploitatie Reservegronden Flevoland* and is the largest organic farm in the Netherlands with 15 employees and hired contract workers. The soil type is silty clay and the field is surrounded by a homogenous intensively farmed arable crop landscape with few natural elements (Kragten and De Snoo, 2008). The average temperature and annual mean rainfall between 1991 to 2020 were 10.5°C and 792 mm (KNMI, 2023). These were 11.7°C and 785 mm in 2020 (KNMI, 2020); 10.4°C and 806 mm in 2021 (KNMI, 2021); and 11.6°C and 729 mm in 2022 (KNMI, 2022).

Field management followed organic regulations, applying no pesticides and only organic manure. Land preparation was done by rotary tiller. Boom irrigation was applied in 2020 and was replaced by drip irrigation installed in 2021. Weeding was done by mechanical harrowing or by hand. Management practices for strip cropping and sole cropping were always the same to make valid comparisons between the two cropping systems. All crops were managed independently of the other crops. There were some variations in field management between the years concerning cultivar choice, irrigation, and sowing and harvest dates (Table 1).

2.2 Experimental design

Prior to the start of the strip cropping experiment in 2020, the field was under sole cropping of cabbages (2017), red beet (2018), and pea (2019). During the experiment, both strip and sole cropping systems followed a fixed crop rotation (Figure 1). The experimental design which includes choices on the strip width, crops and cultivars, and the spatio-temporal configuration of the strips (i.e., temporal crops sequence and spatial allocation of the crops in strips), was co-developed by the farmers and the researchers, with the focus on systematically testing the yield effect of crop neighbors in an applied practical setting. This means that the allocation of crop neighbor was not optimized ex-ante. The choice of strip width was considered based on a management and an agroecological perspectives. While a greater strip width allows for simultaneous and practical management, a narrower width allows for temporal niche differentiation and habitat continuity and contiguity (Landis et al., 2000; Lee et al., 2001; Juventia

TABLE 1 Crop and field management 2020–2022.

Crop	Year	Cultivar	Sowing date	Harvest date	Irrigation	Fertilization
Faba bean	2020	Tiffany	15 April	12 Aug	2×20 mm BI	No additional fertilization
	2021	Cartouch	26 April	14 Sep	20 mm BI	30 m^3/ha slurry before sowing GM
	2022	Macho	21 April	9 Aug	20 mm BI	30 m^3/ha slurry before sowing GM
Broccoli	2020	NA	14, 20 July	21 Sep – 19 Oct	2×20 mm BI	No additional fertilization
	2021	NA	22 May	Sep – Oct	30 mm DI +0 mm BI	30m^3/ha slurry +150 kg/ha OPF 11–0-5 granular
	2022	Marathon, Parthenon, Larsson (±30% each)	5, 14 July	27 Sep – 26 Oct	70 mm total (DI + BI)	30 m^3/ha slurry
Celeriac	2020	Yara	25 May	27 Nov	2×20 mm BI	No additional fertilization
	2021	Calgary	7 June	22 Nov	30 mm DI +20 mm BI	No additional fertilization
	2022	Calgary	23 May	7 Nov	0 mm	No additional fertilization
Grass--clover	2020	NA	20 April	7 July, 2 Sep	2×20 mm BI	No additional fertilization
	2021	NA	22 April	20 July, 20 Sep	0 mm	No additional fertilization
	2022	NA	NA	NA	20 mm BI	No additional fertilization
Oat	2020	Horsch	8 April	10 Aug	2×20 mm BI	No additional fertilization
	2021	Olympic	15 April	24 Aug	20 mm BI	30 m^3/ha slurry before sowing GM
	2022	WPB Elyan	25 March	27 July	20 mm BI	30 m^3/ha slurry before sowing GM
Onion	2020	Centurion, Sturon (±50% each)	2 May	11 Sep	2×20 mm BI	No additional fertilization
	2021	Red baron	22 April	16 Aug	20 mm BI	30 m^3/ha slurry before sowing GM
	2022	Jetset	15 March	1 Aug	20 mm BI	30 m^3/ha slurry before sowing GM
Parsnip	2020	Gladiator	22 May	23 Sep	0 mm	No additional fertilization
	2021	NA	16 June	20 Oct	0 mm	No additional fertilization
	2022	Javalin	1 June	19 Oct	20 mm BI	No additional fertilization
Potato	2020	Allians	24 April	2 Sep	2×20 mm BI	No additional fertilization
	2021	Agria	27 April	16 Sep	30 mm DI +20 mm BI	No additional fertilization
	2022	Allians	26 April	18 Aug	20 mm BI	30 m^3/ha slurry

In 2020 and 2021, the whole field was fertilized with 8 t/ha manure and 5 t/ha chicken manure.
In 2022, 10 t/ha solid cow manure was applied. Additional fertilizer is shown in the table. BI, irrigation with boom; DI, drip irrigation; GM, green manure; NA, data not available.

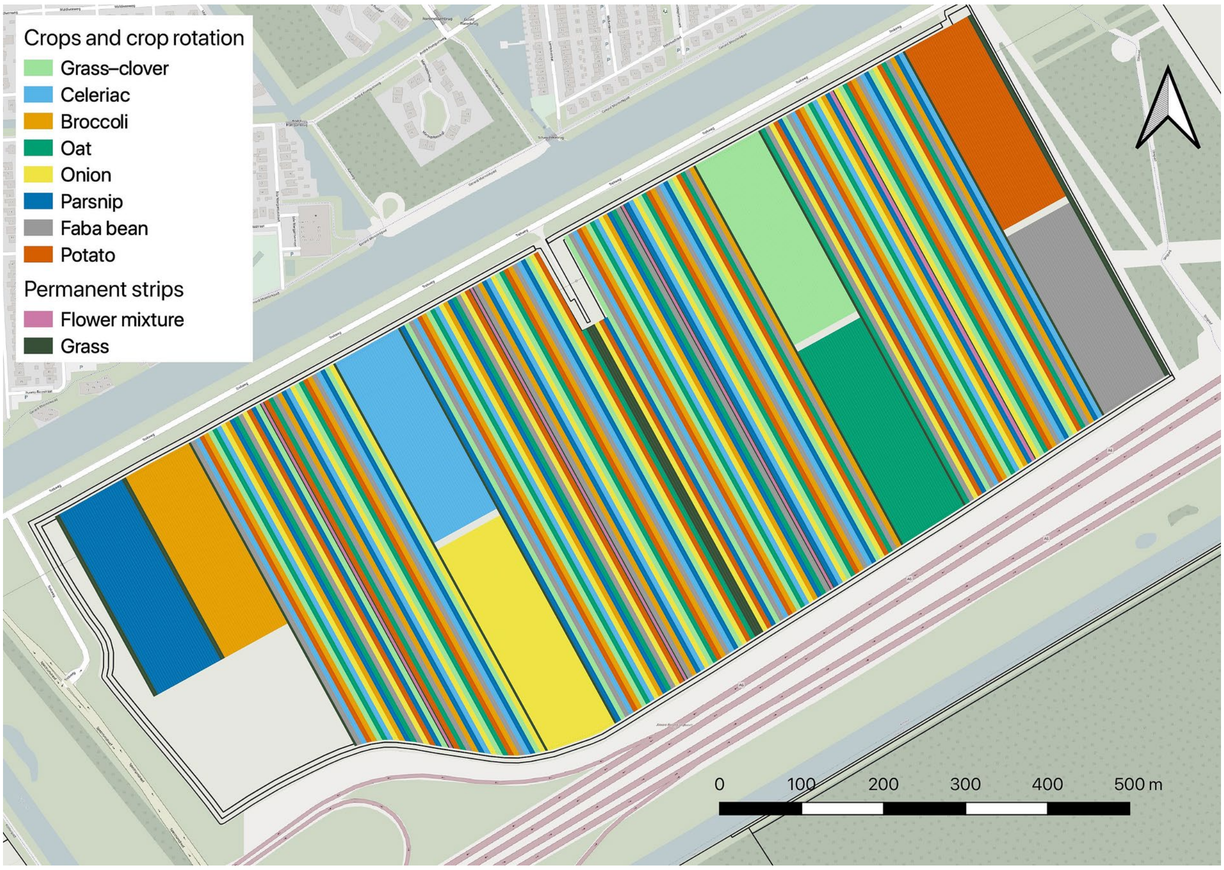

FIGURE 1
Overview of the strip cropping field in 2022. Colors represent the different crops. Each crop was cultivated in four strips per block, which equals a total of 16 strips over the field. Two sole-crop reference plots, each of a 2-ha area, were present per block. The black dashed lines separate the four blocks. The legend represents the sequence of the crop rotation when read from top to bottom.

et al., 2022). A strip width of 6 meters was selected to align with the feasible operational width of the farm's existing machinery. Eight crops were chosen to be grown in an eight-year rotation: grass—clover mixture (*Lollium multiforum* L., and *Trifolium repens* L.), followed by celeriac (*Apium graveolens* var. *rapaceum*), broccoli (*Brassica oleracea var. italica*), oat (*Avena sativa* L.), onion (*Allium cepa* L.), parsnip (*Pastinaca sativa* L.), faba bean (*Vicia faba* L.), and potato (*Solanum tuberosum* L.). In 2020, seed onion was cultivated for plant propagation material, which was changed to plant onion for consumption in 2021. Figure 1 shows the experimental layout which follows an incomplete block design with four blocks, each consisting of two sole crop references, 32 strips, and one perennial grass and flower strip. Across the field, each crop was cultivated in one sole crop reference and 16 strips that neighbor five different crops (Table 2). Per crop, each of the five neighboring crops were present in at least four blocks each year. The incomplete block design allows for comparison of strips with sole crops and of strips with the different crop neighbors across blocks and years.

The crops analyzed in this study were faba bean, celeriac, oat, onion, parsnip, and potato (Table 2). Grass—clover yield was not analyzed as its primary function for the farmers in the rotation is weed control and soil health, but not commercial revenue. Unfortunately, we were not able to obtain reliable yield data on broccoli and therefore this crop was removed from the analyses. Due to weather conditions and market demand broccoli cultivars, harvest moment, and criteria (for fresh market or industry) were changed within the field and years, making comparisons unreliable. All eight crops were included as crop neighbors. The perennial grass and flower strips were excluded as crop neighbors, due to a lack of repetition in the field.

The edge effect of a crop neighbor on yield was analyzed per crop, comparing the yield estimate of a crop on the edge row adjacent to a neighboring crop with its yield on the center row. The strip cropping effect of crops grown in strip versus sole crop was analyzed per crop and across crops, where the yield estimate of each crop grown in the strip was compared with its yield in the sole crop.

2.3 Data collection

Gross harvest yield (i.e., kg fresh harvestable matter per m^2) of the six crops were collected from 2020 to 2022 during the harvest period from August to November. Yield was collected through manual sampling by hand, except for faba bean and oat where machine-harvest data per strip was available (Table 3). Hand-harvest samples were at least 100 meters away from the end of the strip. In 2020, for each crop, samples were collected from each strip at one randomly determined transect perpendicular to the direction of the strips. In 2021 and 2022 this was increased to two transects per strip. Per

TABLE 2 Overview of the experimental setup in 2020–2022 to evaluate the effects of crop neighbors and strip cropping on the yield of the six crops.

Crop	Crop neighbor effect	Strip cropping effect
Faba bean	Center of the strip	Sole crop
	Broccoli	Strip
	Celeriac	
	Grass—clover	
	Oat	
	Onion	
Celeriac	Center of the strip	Sole crop
	Faba bean	Strip
	Oat	
	Onion	
	Parsnip	
	Potato	
Oat	Center of the strip	Sole crop
	Faba bean	Strip
	Celeriac	
	Grass—clover	
	Parsnip	
	Potato	
Onion	Average yield per strip	Sole crop
	Faba bean	Strip
	Broccoli	
	Celeriac	
	Grass—clover	
	Potato	
Parsnip	Center of the strip	Sole crop
	Broccoli	Strip
	Celeriac	
	Oat	
	Grass—clover	
	Potato	
Potato	Center of the strip	Sole crop
	Broccoli	Strip
	Celeriac	
	Oat	
	Onion	
	Parsnip	

Each crop neighbors five other crops. For onion, the average yield per strip was used in evaluating the crop neighbor effect as the yield of the center row was not available (see section 2.3).

transect, three positions were sampled with exception for onion. In the strip, one center row and two edge rows were sampled, while in the sole crop, these were the three rows in the center of the sole crop reference. For onion, two swaths from the western half of the strip (i.e., the 1st-4th rows) and the eastern half (i.e., the 5th-8th rows) were sampled following mechanical lifting which lifted the onions from the ground and formed the two swaths. The sampling area per crop differed as this was based on the planting density of the crop and for reasons of feasibility (Table 3). The total fresh weight of the produce per sampling area was measured using a field scale, from which yield per unit area was calculated.

2.4 Data analyses

2.4.1 Relative yield to evaluate crop neighbor and strip cropping effect

Relative yield (RY), i.e., the ratio of intercrop to the reference yields (Willey, 1979), was calculated to evaluate the effect of crop neighbors and strip cropping. To analyze the crop neighbor effect, the center row within the strip was used as the reference as in Equation 1:

$$Relative\ yield_{crop\ neighbor} = \frac{IYie}{IYim} \qquad (1)$$

where *IY* is the intercrop fresh weight per unit area of the crop *i*. The *e* represents the edge row of crop *i* adjacent to a crop neighbor, while *m* represents the center row from the same strip of the crop *i*. Given that each crop neighbors five other crops (Table 2), five $RY_{crop\ neighbor}$ values per crop were calculated. An edge effect is present when $RY_{crop\ neighbor}$ is significantly different from one.

The effect of strip cropping was analyzed per crop and across the six crops using Equation 2:

$$Relative\ yield_{strip\ cropping} = \frac{IY}{SY} \qquad (2)$$

where IY is the intercrop fresh weight per unit area and SY is the sole crop yield. For faba bean (2020–2021) and oat (2020–2022), machine-harvest yield per strip-and sole-cropped area was used. For all other crops where samples were collected by hand-harvest, only the yield from the center rows were included in analyzing the strip cropping effect as the center rows were considered to be representative of the yield per strip or sole crop (see Table 3). The absolute yields per year and per crop in both strip and sole crop systems are provided in Supplementary Table S4B. A strip cropping effect is present when $RY_{strip\ cropping}$ is significantly different from one.

2.4.2 Alternative spatial configurations

To facilitate the focus of this experiment which was to systematically test the yield effect of as many crop neighbors as possible in an applied practical setting, two distinct sub-configurations (i.e., sub-configurations #1 and #2, Supplementary Figure S1) were combined into one configuration—the current experimental design (Figure 1). Both sub-configurations followed the same crop rotation and honored the 'hop-skip-jump' principle after Vereijken (1997), such that a crop is not planted in a strip adjacent to where it was last year, in order to create discontinuity for pest and disease in space (Juventia et al., 2022). While in sub-configuration #1 each crop had four neighbors, in sub-configuration #2 each crop neighbored three crops. Each of this sub-configuration was then used to build the alternative spatio-temporal configurations #1 and #2, respectively (Supplementary Figure S1).

TABLE 3 Gross harvest yield data per crop collected in the period 2020–2022.

Crop	Year	Method	Area (m^2)	Rows	Number of samples
Faba bean	2020	Machine	Per strip/ per sole crop	All rows	31
	2021	Machine	Per strip/ per sole crop	All rows	42
	2022	Hand	1	Strip: 1, 6, 12; Sole crop: 47, 50, 53	84
Celeriac	2020	Hand	1.5	Strip: 1, 7, 12; Sole crop: 45, 46, 47	45
	2021	NA due to crop failure			
	2022	Hand	1.5	Strip: 1, 7, 12; Sole crop: 45, 46, 47	96
Oat	2020	Machine	Per strip/ per sole crop	All rows	15
	2021	Machine and hand	Machine: Per strip/ per sole crop; Hand: 0.25	Machine: all rows; Hand: Strip: 1, 6, 12; Sole crop: 47, 50, 53	27 (machine), 84 (hand)
	2022	Machine	Per strip/ per sole crop	All rows	28
Onion	2020	Hand	9	Strip: 1–4 and 5–8; Sole crop: 53–56 and 57–60	28
	2021	Hand	9	Strip: 1–4 and 5–8; Sole crop: 53–56 and 57–60	58
	2022	Hand	9	Strip: 1–4 and 5–8; Sole crop: 53–56 and 57–60	60
Parsnip	2020	Hand	2.25	Strip: 1, 4, 8; Sole crop: 31–33	45
	2021	Hand	2.25	Strip: 1, 4, 8; Sole crop: 31–33	84
	2022	Hand	2.25	Strip: 1, 4, 8; Sole crop: 31–33	84
Potato	2020	NA due to inconsistent sampling method (center rows not sampled)			
	2021	Hand	2.25	Strip: 1, 4, 8; Sole crop: 53, 55, 57	94
	2022	Hand	2.25	Strip: 1, 4, 8; Sole crop: 53, 55, 57	90

Method indicates sample collection method, either machine-or hand-harvest. Area represents the sampling area per sample. Rows indicate the nth row from which the samples were collected within the strip or the sole crop reference. The 1st row (western edge) and the 8th or 12th rows (eastern edge, depending on the crop) are directly adjacent to the crop neighbor. All other rows represent the center row in the strip or the rows at the center of the sole crop.

2.4.3 Performance of the current and alternative configurations

Using the gross and relative yield data, we evaluated the overall performance of strip cropping on three indicators: (1) land saving proportion, (2) relative gross revenue, and (3) breakeven labor cost ratio. We compared the current experimental design (Figure 1) and the two alternative spatio-temporal configurations (Supplementary Figure S1).

2.4.3.1 Land saving proportion

The land equivalent ratio (LER) is one of the most frequently used indicators of productivity in intercropping studies because it captures in a single value the land area that might be saved by intercropping instead of sole cropping (Van der Werf et al., 2021). LER represents the ratio of land area needed under intercropping to the area of sole cropping to obtain an equal amount of yield at the same management level (Mead and Willey, 1980; Vandermeer, 1989). LER was calculated based on the fresh yield of the six crops across the 3 years of the experiment using Equation 3:

$$LER_j = \sum \frac{IYimj}{SYi} \tag{3}$$

where IY is the intercrop fresh weight from the center row m per unit sole-crop area of crop i in strip configuration j and SY is the sole crop yield of crop i. LER > 1 means that the strip was more efficient in terms of land use compared to the sole crop. We calculated the LER for the current and alternative configurations. To evaluate the change in yield with respect to land required we calculated the associated land saving proportions for the current and alternative configurations using Equation 4 (Khanal et al., 2021; Van der Werf et al., 2021).

$$Land\ saving\ proportion = \frac{LER - 1}{LER} = 1 - \frac{1}{LER} \quad (4)$$

The proportion of land saved could be used for inclusion of non-productive elements of semi-natural habitats in or around the field like flower strips or hedgerows for increasing biodiversity (Bianchi et al., 2006; Sirami et al., 2019; Guo et al., 2022).

2.4.3.2 Relative revenue

Different crops usually have different monetary values, making it valuable to also compare total revenues (Khanal et al., 2021). Here we used the farm-gate selling price of each crop (Table 4) and calculated the relative total value (i.e., relative revenue) per unit area for the different strip cropping configurations and the sole crop using Equation 5:

$$Relative\ revenue_j = \frac{\sum(IYimj \cdot Pi)}{\sum(SYi \cdot Pi)} \quad (5)$$

where IY is the intercrop fresh weight from the center row m per unit sole-crop area of crop i in strip configuration j, SY is the sole crop yield of crop i, and P is the price of crop i. Here we assumed that the total gross harvest yield can be sold, not taking into account storage losses or difference in quality between treatments. Selling price was used to apply weight so as to complement the use of LER which has been criticized for failing to account for the different magnitude of changes in the yield of one crop component of an intercrop and in another (Khanal et al., 2021). An increase in relative revenue could be used for various purposes, such as allocating non-productive nature-inclusive areas, investing in new technologies, or addressing implementation challenges associated with strip cropping, thereby facilitating its broader adoption.

2.4.3.3 Breakeven labor cost ratio

An increase in labor is often identified as one of the implementation challenges of a strip cropping system (Rosa-Schleich et al., 2019; Al-Amin et al., 2024). Hence, a breakeven labor cost ratio might be a good proxy to indicate the feasibility of implementing strip cropping. The breakeven point indicates where the difference in revenues between the strip and the sole cropping breaks even with the additional labor cost associated with strip cropping operations (Equation 6). From there, by dividing both sides by the sole crop labor cost (Equation 7), we calculated the breakeven labor cost ratio (Equation 8). This ratio shows how much of the increased labor cost from strip cropping can be offset by the extra revenue generated, making the practice economically viable.

$$\Delta labor\ cost_{strip-sole} = \Delta gross\ revenue_{strip-sole} \quad (6)$$

$$\frac{\sum(IHij \cdot w) - \sum(SHi \cdot w)}{\sum(SHi \cdot w)} = \frac{\sum(IYimj \cdot Pi) - \sum(SYi \cdot Pi)}{\sum(SHi \cdot w)} \quad (7)$$

$$Breakeven\ labor\ cost\ ratio_j = \frac{\sum(IHij \cdot w)}{\sum(SHi \cdot w)} = \frac{\sum(IYimj \cdot Pi) - \sum(SYi \cdot Pi)}{\sum(SHi \cdot w)} + 1 \quad (8)$$

where IH and SH are the total hours spent across field operations of crop i in strip configuration j and sole cropping respectively, w is the average labor cost per hour, IY is the intercrop fresh weight from the center row m per unit sole-crop area of crop i in strip configuration j, SY is the sole crop yield of crop i, and P is the price of crop i. For calculating labor requirements of sole cropping ($SHi \cdot w$), ERF B.V. uses standard reference values of *Kwantitatieve Informatie Akkerbouw en Vollegrondsgroenteteelt* (KWIN) (Van der Voort, 2022). KWIN reports for each crop, the total number of hours spent on average per field operation (e.g., soil preparation, sowing/planting, irrigation, fertilization, harvesting, etc.) and the average labor cost per hour (40.53€/hour) in the Netherlands. The total number of hours spent across various field operations is shown in Table 4.

TABLE 4 Average farm-gate selling price, labor hour, and labor cost data per crop as reported by the farm.

Crop	Selling price (€/kg)	Labor hour (hour/ha)	Labor cost (€/ha)
Faba bean	0.61	20.0	810
Celeriac	0.22	151.6	6,140
Oat	0.33	17.8	720
Seed onion	2.00	123.5	5,000
Onion	0.60	38.0	1,540
Parsnip	0.50	98.2	3,980
Potato	0.38	44.0	1,780

Seed onion was excluded from the revenue analyses given its unusually high price in 2020. The labor hour sums the total number of hours spent across various field operations in a growing season. Labor cost is rounded down to nearest multiply of 10.

2.5 Statistical analyses

For each crop, linear mixed-effect models (LMMs) were developed separately to assess the effect of crop neighbors and strip cropping on the response variable yield. To assess the effect of crop neighbors, the identity of the 'crop neighbor' was used as a fixed effect (Supplementary Table S2A). To assess the effect of strip cropping, strip or sole-crop 'treatment' was used as a fixed effect (Supplementary Tables S2B–C). The variable 'year_block' was included as random effect, to account for the combined effect of temporal and spatial variability across the 3 years and within the field. Model selection was based on the Akaike Information Criterion (AIC). Statistical analyses were conducted using one-way analysis of variance (ANOVA) and Sidak post-hoc test. We used the Shapiro–Wilk Normality test on the residuals (Shapiro and Wilk, 1965) and visual analysis of the QQ plots using the DHARMa package (Hartig, 2022) to confirm that the normality assumption was met. All analyses were performed using the R program, version 4.0.2 (R Core Team, 2020), and the lme4 package (Bates et al., 2015).

Model estimates were then used to calculate the $RY_{crop\ neighbor}$ which compared the yield of the edge row compared to the center row of the strip, and the $RY_{strip\ cropping}$ which compared the yield of the strip to the sole crop. This resulted in the RY of the referenced system (i.e., either the center row of a strip or the sole crop) always equals 1.

3 Results

3.1 Relative yield

3.1.1 Effect of crop neighbors on yield per crop

When analyzed across all crop neighbors (Supplementary Figure S3), a significant edge effect was observed for potato and celeriac, where higher yield was observed on the edge row of potato than the center row, and the other way around for celeriac (Supplementary Table S4A). Edge effect by specific crop neighbors was observed on faba bean and potato (Figure 2). The RY of the faba bean rows adjacent to broccoli and celeriac were significantly higher by 68 and 73% than the faba bean row next to onion ($p < 0.001$). Potato showed a higher RY by 15 to 38% when neighboring celeriac and broccoli compared to potato on the center row or when neighboring oat ($p < 0.001$).

3.1.2 Effect of strip cropping on yield per crop and across crops

Strip cropping effect varied with year in both systems for all the crops, except celeriac and onion (Supplementary Tables S2, S4B). Across the years, a significant effect of strip cropping was observed on the RY of faba bean, oat, onion, and parsnip ($p < 0.05$) (Figure 3). For faba bean and parsnip, RY was increased by 32 and 41%, respectively, in the strip compared to the sole crop. In contrast, the RY of oat and onion were lower by 6 and 10%, respectively, when cultivated in strips. When analyzed across all crops, an overall 8% higher relative yield was observed in the strip than in the sole crop ($p < 0.001$).

3.2 Performance of the current and alternative configurations

The current and alternative configurations resulted in LER and relative revenue higher than 1 (Table 5). LER values ranged from 1.06 to 1.11, translating to land saving proportions ranging between 5 to 10% by strip cropping to produce the same yield as in the sole crop. The current experimental design yielded a gross revenue of 12,150 €/ha while the sole crop yielded 11,560 €/ha. This means that an extra revenue of 590€/ha can be earned by strip cropping (i.e., relative revenue equals 1.05), which can accommodate a 24% increase in labor cost (i.e., breakeven labor cost

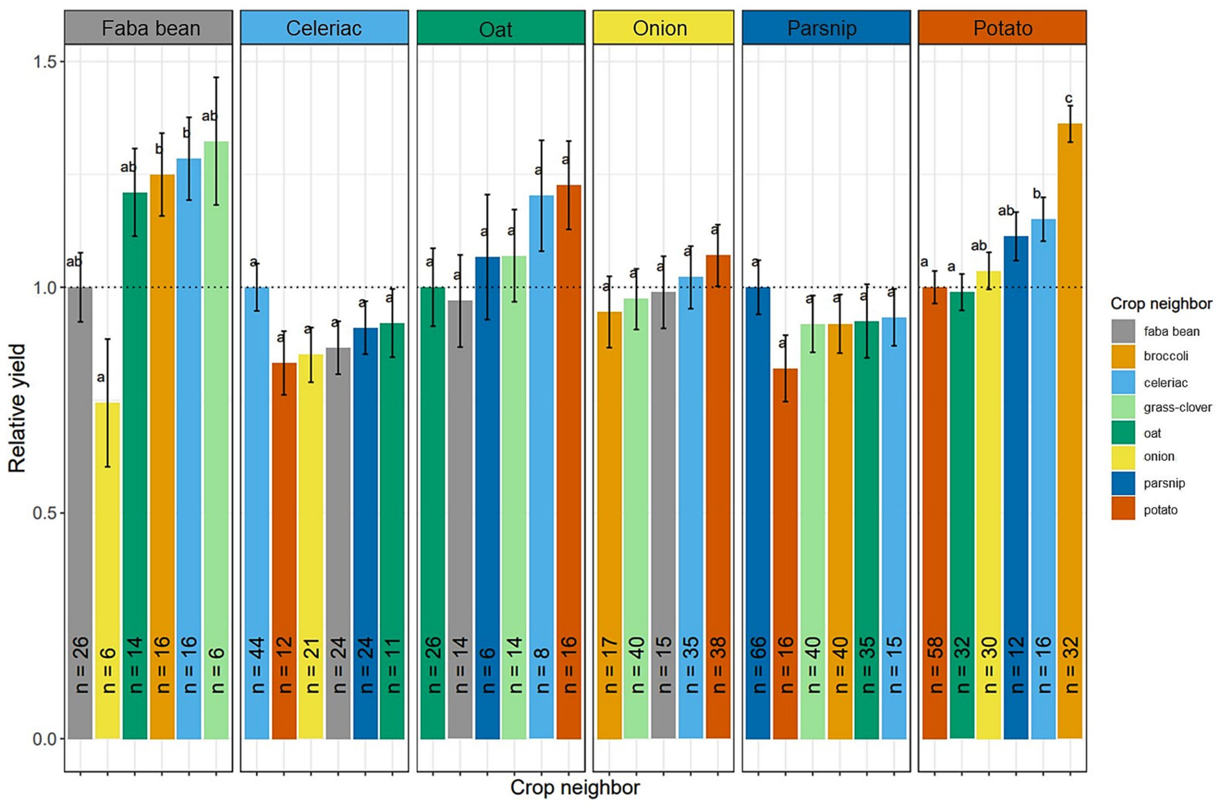

FIGURE 2
The relative yield of the six crops, comparing the edge rows that neighbor different crops to the center row. Bar color corresponds to the color of the crops presented in the legend and the field map (Figure 1). The RY of the center row which always equals 1 is represented by the first bar on the left side of each panel. For onion, the bar for the center row is absent since the average gross harvest yield of the two swaths per strip was used to calculate RY (see 2.3). Error bars indicate standard error. Letters indicate significant differences between the crop neighbor effects for each crop ($p < 0.05$). Sample sizes per crop neighbor are shown at the bottom of each bar.

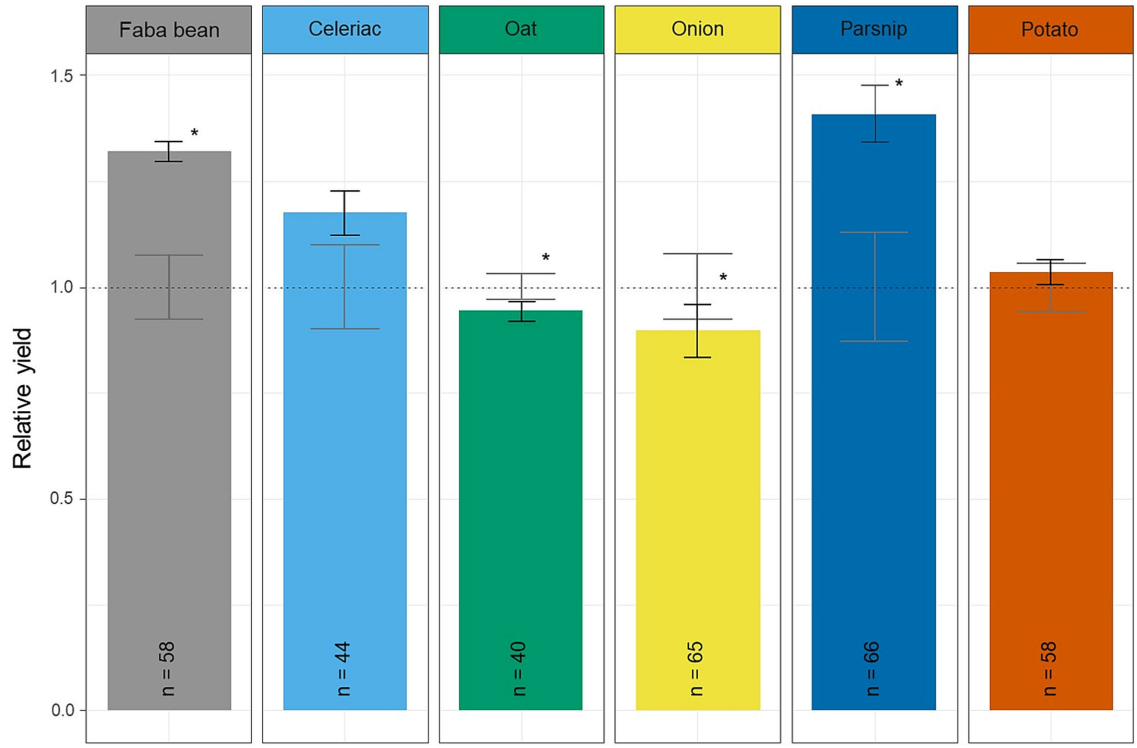

FIGURE 3
The relative yield of the strip compared to the sole crop for the six crops from 2020 to 2022. Bar color corresponds to the color of the crops presented in the field map (Figure 1). The RY of the sole crop which always equals 1 is represented by the dotted line. Error bars indicate the standard error of the strip (in black) and the sole crop (in grey). Asterisks indicate significant differences between the cropping systems ($p < 0.05$). Sample sizes per crop are shown at the bottom of each bar.

TABLE 5 Performance of the current experimental design and the two alternative configurations in terms of LER, land saving proportion, relative revenue, and breakeven labor cost ratio.

Configurations	LER	Land saving (%)	Relative revenue	Breakeven labor cost ratio
Current experimental design	1.08	7.7	1.05	1.24
Alternative configuration #1	1.06	5.3	1.04	1.17
Alternative configuration #2	1.11	10.0	1.07	1.30

ratio equals 1.24). Alternative configuration #2 showed a higher LER and an extra revenue of 759€/ha compared to the current design.

4 Discussion

4.1 Summary of findings

This study aimed to evaluate the effects of crop neighbors and strip cropping on yield and explore if optimizing the allocation of crop neighbors in alternative strip cropping configurations can improve yield and revenue performances. Only potato next to broccoli and celeriac showed an edge effect when comparing the edge row and the center row within a strip. We observed positive strip cropping effect in faba bean and parsnip and negative effect in oat and onion when comparing center row yield in strip with sole crop reference. Examining the overall performance of the strip cropping system across crops at the cropping system level revealed an overall positive strip cropping effect on yield. Alternative configuration #2 showed a higher LER and relative revenue compared to the current experimental design and the other alternative configuration.

4.2 Limited effects of crop neighbors

While the literature is sparse when it comes to the performance of specific crop combinations, we found that for oat, our result was consistent with Ghaffarzadeh et al. (1994) who observed non-significant but higher yield ($p = 0.1$) in the edge rows neighboring corn and soybean than in the center row. For potato, temporal niche differentiation due to the later sowing date of the parsnip, celeriac, and broccoli as neighboring crops may explain the trend of higher yield in the edge rows (Table 1). In 2022, the significantly higher potato yield on the edge row neighboring broccoli might be explained by the application of drip irrigation in the broccoli strip, while no irrigation was applied in the potato strip (Table 1).

One plausible reason for the limited edge effect is that positive effects are compensated by negative effect between the neighboring crops due to foliage damage at the strip border due to mechanization (Ghaffarzadeh et al., 1994; Seehusen et al., 2014). Only for potato a significant difference between yield in the edge row relative to the center row was observed despite reasonable sample size and effect size. We speculate that this might be due to the scale of observations (approximately 10 plants per sample) being insufficient to capture the variation caused by the different crop neighbors. The variation between the individual samples that neighbored the same crop was too large and could not be fully accounted for by including the variable 'block_year' and/or 'transect' as random effects in the linear mixed-effect models. The scale of large-scale systems as in this study might require sampling and/or analyzing techniques beyond plot scale. For instance, collecting yield samples from a larger area along the strip, or reducing variation between samples by accounting for spatial patterns from for example soil organic matter may allow capturing and detecting (potentially) significant effects of crop neighbors.

4.3 Significant effects of strip cropping for several crops

The effect of strip cropping compared to the sole crop was positive for faba bean and parsnip, and negative for oat and onion. The significantly higher faba bean yield in strips was in accordance with Luo et al. (2021) who observed around 30% overyielding of faba bean next to wheat. The increase in parsnip yield, however, was not aligned with the one-year experiment result in South Holland where no significant effect was observed (Hondebrink et al., 2019). The significantly lower oat yield in strips also contradicted Głowacka (2014) who found an increased grain number and weight per panicle due to positive edge effects next to corn and lupin in strips of 3.3 meters. For onion, the significantly lower yield in strips was consistent with several other studies (Broad et al., 2004; Motagally and Metwally, 2014; Luqman et al., 2020). This might be due to the low competing ability of onion against interspecific competition for light and below-ground resources, especially early in the season (Dunan et al., 1996; Ndjadi et al., 2022).

Surprisingly the inner rows in a 6-meter strip performed significantly differently than the sole crop reference. This might be because the crop neighbor effect on the edge rows of the strip seemed to be limited and the edge rows in our experiment only constitute up to one-quarter of the yield per strip. As postulated by Wang et al. (2020), the strip width, and thus the proportion of edge rows to the inner rows, determines the strength of the resulting relative yield: the higher the proportion of edge rows in a strip with a narrower width, the stronger the edge effect on the yield will be.

In the inner rows, a positive strip cropping effect might arise due to microclimate and/or reduced intraspecific competition from the poorly performing plants on the edge rows that suffer from higher interspecific competition. This might explain the higher yield observed in the center compared to the edge row for celeriac (Supplementary Table S4A). Perhaps similar to the mechanism in agroforestry or alley cropping systems, the modification of microclimate in terms of temperature, water distribution, and air movement, reduces heat and evaporative stress on the crops, thereby increasing the crop yield (Jose et al., 2004). This was often observed in the crop rows further away from the trees, where the potentially positive microclimate effect outweighs the crop-tree interspecific competition (Borin et al., 2010; Van Vooren et al., 2016).

A positive effect on yield might also arise due to the lower pest and disease pressure in strips. The potential for strip cropping to increase parasitism rate and reduce crop injury by herbivorous pests has been shown in strip-cropped cabbage, although the correlation between herbivore abundance and yield was not always consistent (Juventia et al., 2021; Croijmans, 2024; Croijmans et al., 2024). Similarly, lower *Phytophthora infestans* infection on potato was found in 3 m and 6 m wide strips. However, broccoli was excluded from the yield analysis and for potato, no difference in relative yield of strip compared to the sole crop was observed.

4.4 Significant effects of strip cropping across crops

A more pronounced strip cropping effect was observed when analysis was done at a higher aggregation level at the cropping system level across crops rather than per individual crop. There was an overall significantly positive effect, although only four out of six crops showed significant difference, two of which were positive and two were negative. The overyielding in parsnip, faba bean, and celeriac although not significant, apparently outweighed the under-yielding in onion and oat. This effect that was observable when the analysis was conducted across crops, indicates the value of observation at the cropping system level to evaluate the effect of strip cropping systems in practical settings and capture their potential.

4.5 Alternative strip cropping configurations

The current strip cropping design, which was co-developed by the farmers and the researchers, was aimed to systematically test the yield effect of crop neighbors, without optimizing their spatial allocation ex-ante. Alternative configuration #2 showed higher LER and relative revenue than those of the current experimental design and alternative configuration #1. Here the temporal effect of crop rotation was assumed to be the same as both the current and alternative configurations were based on the same crop rotation.

Exploring alternative crop rotations and subsequently alternative spatio-temporal strip cropping configurations using tools such as the ROTAT and RotaStrip as proposed in Dogliotti et al. (2003) and Juventia et al. (2022) could improve performance (LER equals 1.2, Supplementary Figures S5A,B). In this exploration each of the eight crops only neighbors two other crop neighbors (instead of five as in the current design, four in alternative configuration #1, or three in alternative configuration #2) such that these newly generated configurations comprise less of the lower-yielding combinations of crop neighbors. However a different crop rotation would be required for these newly generated configurations and its effects cannot be fully predicted since the temporal effect of the new crop rotation might outweigh the spatial configuration effect. As there might be trade-offs between temporal effects of rotation and spatial effects of the crop neighbor configurations, future studies should take both into account when designing strip cropping systems to optimize its performance.

4.6 Performance of the current and alternative strip cropping configurations

The advantage of the current design and alternative configurations in terms of LER that was higher than 1 (1.06–1.11) was consistent with a simulation study by Van Oort et al. (2020) and a meta-analysis on intercropping systems in Europe (Yu et al., 2015). However, our values were lower compared to previous studies that reported a strip cropping LER of 1.3 in Asia (Yu et al., 2015) and 1.49 globally (Zhu et al., 2023). LER advantage was shown to decrease under high nutrient input relative to low input (Zhu et al., 2023). This could explain our relatively lower LER values as the system studied here can be considered to be input-intensive, where nutrient application rates surpassed those in other regions globally (Lassaletta et al., 2014 in Silva et al., 2021). The 7.7% of land saved could be used to compensate for the area lost due to increased area needed for headlands or for semi-natural habitat such as flower strips within or around the field (currently taking up 3% of the strip cropping fields), so as to increase general biodiversity and pest control (Bianchi et al., 2006; Hatt et al., 2017).

The result of economic evaluation in terms of relative revenue, where the different magnitude of changes in the yield of the different crops were weighted using the farm gate price, was consistent with the LER evaluation result. The alternative configurations showed relative revenue higher than one, although lower than 1.33, the value from a global meta-analysis on intercropping systems (Martin-Guay et al., 2018). Even in the case of the lowest performing newly generated configurations, the increase in revenue of more than 500€/ha was higher than the maximum Common Agricultural Policy (CAP) additional eco-scheme subsidy in 2023 of 200€/ha that can be received through a combination of practices (e.g., strip cropping, flower strips, rest crops, alley cropping etc.) (European Commission, 2021a, 2021b; RVO, 2022).

The increase in gross revenue could be used to invest in technologies adapted to intercropping systems (Mamine and Farès, 2020; Ditzler and Driessen, 2022) and to cover potentially up to 25% increase in labor cost that may be incurred due to strip cropping. The scale of the field and experience of the farmer potentially led to no observed increase in labor costs. Other farmers associated strip cropping with more working hours due to, for example, more driving in/between the fields, more time needed for the strategic planning phase, and a higher labor demand for hand weeding when the choice of (narrow) strip width does not allow for mechanical/chemical weeding. More thorough cost–benefit and labor use efficiency analyses would be useful to assess the economic prospects of strip cropping implementation (Huang et al., 2015; Serebrennikov et al., 2020). Future studies should also take into account the potential benefit of strip cropping systems in terms of product quality and its associated price classes (e.g., higher price for fresh market quality than industry), which in turn will further improve the revenue (Juventia et al., 2021) to increase its economic feasibility.

4.7 Usefulness of the study and recommendation for future studies

The present study responds to the growing need by current and aspiring farmers, advisors, and engaged researchers in the strip cropping network in the Netherlands by bridging the knowledge gap on what constitutes good crop combinations (Isbell et al., 2017; Juventia et al., 2022), beyond plot-level scale and across seasons (Ditzler et al., 2021a). We expanded the focus beyond cereal-legume intercropping (Stomph et al., 2019) to widen the range of crop choices for strip cropping implementation. This is relevant as farmers in the Netherlands often opt for the spatially most complex 'All crops' configuration type which involves at least four crops, each neighboring two or more neighbors (Juventia et al., 2022). While further research and experience is needed to understand what constitute optimal crop combinations, the positive effect of strip cropping on yield and revenue, even without optimized spatial allocation suggests that the positive effect from the overall increase in diversity in the strip cropping system may compensate for the suboptimal neighbors. This may facilitate farmers to experiment with strip cropping systems. Lastly, similar to the finding by Ditzler et al. (2023), our study suggests that understanding the potential of crop diversification including strip cropping requires an evaluation at the cropping system level across crops, in addition to evaluating the effect per individual crop. This might be more evident in our study, which involved eight crops under strip cropping, than in other intercropping studies consisting of only two crops.

5 Conclusion

Currently empirical studies on what constitutes optimal crop combinations for yield in (strip) intercropping arrangements are limited. We were not able to detect edge effects on yield, with the exception for potato. When comparing the yield in strips to those in the sole crop, strip cropping yielded higher for faba bean and parsnip, and lower for oat and onion. However, when analyzed across crops, strip cropping increases both the overall yield and revenue. The proportion of land saved and the increased revenue gained by strip cropping could be used to offset the area lost to headlands or non-productive semi-natural habitats, invest in technologies adapted to strip cropping, and/or cover additional labor cost associated with it. This result especially showed the benefits of crop diversity beyond individual crop-by-crop comparison. The positive but variable strip cropping effects observed in the current experimental design and the two alternative configurations suggests prioritizing an overall increased crop diversity over optimizing their spatial arrangement. The lack of edge effect, along with the current inability of explain the mechanisms behind the observed strip cropping effects, suggests that the practical management considerations might be more important than focusing solely on yield optimization in determining crop neighbors. Further experience is needed to populate the database on what constitutes good crop combinations beyond yield performance and to test the effect of various designs in different farm contexts. This would foster the wider adoption of strip cropping in the Netherlands and Western Europe.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

SJ: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. DA: Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. This project was financially supported by the TKI Agri & Food [grant number LWV19129] paid part of salary and experimental costs of SDJ and DvA, POP-3 [ZL-00442] paid for part of salary SDJ and CropMix [NWA.1389.20.160] paid for salary DvA.

Acknowledgments

We thank the two reviewers for their constructive feedback. We extend our gratitude to the ERF B. V. farm managers, Roy Michielsen and Dirk van de Weert, who made this work possible. We are grateful to the Unifarm staffs, colleagues, and the many students who contributed to the yield data collection. These include: Jelle Jolink, Joep Laan, Peter van der Zee, Bas Jonkers, Dirk Bloed, Frans Bakker, Wim Lieftink, Laura Riggi, Jiali Cheng, Andi Dirham Nasruddin, Titouan Le Noc, Marieke Datema, Cecillia Revol, Adham Muhammad, Anna de Rooij, Paolo Pezzolla, Pepijn van Hees, Julia Mechelse, Tom van Dijk, and Junjie Xu.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2024.1452779/full#supplementary-material

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TYPE Original Research
PUBLISHED 11 November 2024
DOI 10.3389/fsufs.2024.1449615

OPEN ACCESS

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RECEIVED 15 June 2024
ACCEPTED 02 September 2024
PUBLISHED 11 November 2024

CITATION
Fuchs LE, Orero L, Kipkorir L, Apondi V and Owili SO (2024) Scaling models for Regreening Africa: enhancing agroecological integration through smallholders' assets and agency in Kenya.
Front. Sustain. Food Syst. 8:1449615.
doi: 10.3389/fsufs.2024.1449615

Scaling models for Regreening Africa: enhancing agroecological integration through smallholders' assets and agency in Kenya

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Urgent action is needed to address climate change, land degradation, and biodiversity loss. The Regreening Africa project (2017–2023), recently recognized as a UN World Restoration Flagship, aimed to reverse land degradation over large areas of land for the triple benefit of people, biodiversity, and climate in eight African countries. Based on projections and early lessons learned, the project sought to identify sustainable scaling models to achieve its ambitious targets. The so-called "Asset-Based Community-driven Development (ABCD) in Regreening" project aimed to demonstrate the positive contribution of deliberate community engagement and co-design. The project introduced ABCD sessions to 30 purposively selected community groups in the Regreening intensification sites in western Kenya. ABCD combines a unique set of framings, methods, and processes that focus on people's assets and agency, and emphasizes the importance of their attitudes toward self and others for sustainable behavior change. To evidence that ABCD *intrinsically* contributes to sustainable adoption and scaling of Regreening practices, the project developed the F-ACT+ tool to assess the alignment between ABCD and agroecological practices, and collected baseline and endline data from 300 project and 300 non-project participants. Results showed accelerated agroecological integration among ABCD project participants. ABCD participants showed significant improvements in nine agroecological principles and eight system components, particularly in the economic diversification, social values and diets, and knowledge co-creation principles, as well as in the pest and disease, household, and value chain system components. Summary ATT between ABCD and non-ABCD respondents was positive and significant in 10 principles and eight system components. The results support the synergistic contribution of ABCD to projects targeting sustainable behavior change at the individual and collective levels. Due to its focus on outcomes, this study provided limited insight into the specific mechanisms of ABCD, which are the subject of a separate publication on parallel theory-based contribution analysis work.

KEYWORDS

Regreening Africa, agroecology, agency, land restoration, asset-based community development, ABCD, sustainable scaling

1 Introduction

With six of the nine planetary boundaries being crossed (Richardson et al., 2023), urgent action is needed to combat climate change, land degradation, and biodiversity loss, and to address food and nutrition security in an inclusive and equitable manner. One such large-scale restoration project is the Regreening Africa project. Recognized as a UN World Restoration Flagship in February 2024, the project was implemented in eight African countries, including Senegal, Mali, Niger, and Ghana in West Africa, and Rwanda, Kenya, Somalia, and Ethiopia in East Africa from 2017 to 2023, with funding from the European Union. The goal of the project was "to restore large areas of land for the triple benefit of people, biodiversity, and climate" (Bourne, 2024). In Kenya, the project aimed to reverse land degradation on 150,000 ha of farmland and to encourage 50,000 smallholder farmers to adopt sustainable restoration practices over 5 years. The project aimed to engage 20% of them through direct interventions (Regreening Africa, 2018).

Although the targets acknowledged the need for sustainable land restoration by land stewards, mobilizing 10,000 farmers for long-term behavior change was challenging, particularly because it required long-term behavior change (Regreening Africa, 2018). Regreening Africa's baseline study also identified barriers to successful land restoration at the local level, including biophysical, socio-economic, and behavioral factors. Key biophysical factors included land degradation, climate change, limited access to water, and limited access to high quality seeds and germplasm. Socio-economic barriers included inadequate markets and investment, limited policy enforcement, and insecure land tenure, while some of the behavioral factors included women's limited decision-making power, as well as negative perceptions about the role and impact of restoration, about trees competing with crops, and about time lags in financial returns from restoration (Hughes et al., 2020). Given these predictions and early experiences, Regreening Africa actively sought to identify sustainable scaling models that could support achieving the project targets in Kenya and could potentially be replicated in the other project sites. In response to this challenge, the CIFOR-ICRAF teams focusing on Regreening Africa, and Asset-Based Community-driven Development (ABCD) collaborated on the so-called "ABCD in Regreening" project. The project was implemented from 2021 to 2023 in Homa Bay County, which was one of the Regreening Africa intensification sites. The project and its primary objective join other efforts in agricultural research and policy in recent decades that seek to investigate the drivers of adoption decisions and behavior change (e.g., Arslan et al., 2022; Ewert et al., 2023; Knowler and Bradshaw, 2007; Nikiema et al., 2023; Pannell et al., 2006; Prokopy et al., 2008). Specifically, rather than looking at socio-economic or behavioral determinants, this study contributes to the body of work investigating the effects of intentional engagement, knowledge co-creation, and extension processes (e.g., Glover et al., 2019; Lukuyu et al., 2012; Wossen et al., 2017). In the context of this project, we further consider scaling in terms of engaging "more people over a wider geographical area, more quickly, more equitably, and more lastingly" (Gonsalves, 2000, p. iv).

ABCD builds on people's agency and capacity. The approach was first theorized and popularized by Kretzmann and McKnight (1993, 2005) at the Institute for Policy Research at Northwestern University in Illinois, USA, as a strategy for empowering marginalized groups and neighborhoods in the inner cities of the United States. They have continued to lead the global conversation on ABCD through the ABCD Institute, established at Northwestern University in 1995 and consolidated at DePaul University in Chicago in 2016(e.g., McKnight, 2014; McKnight and Block, 2012; McKnight, 2009; McKnight and Russell, 2018; McKnight and Russell, 2022). In the early 2000s, the Coady Institute at St. Francis Xavier University in Antigonish, Nova Scotia, Canada, adapted ABCD to international development contexts (Cunningham et al., 2018; Ghore, 2015; Mathie et al., 2017; Mathie and Cunningham, 2003, 2008; Mathie and Peters, 2014; Peters et al., 2011; Peters and Eliasov, 2013), and it has been adopted by many institutions and actors around the world. ABCD draws on and aligns with numerous theoretical and conceptual sources, including the field of appreciative inquiry (Ashford and Patkar, 2001; Elliott, 1999), "positive deviance" (Tufts University, P. D. I, 2010), the sustainable livelihoods approach (DfID, 1999), the theory and practice associated with community economic development and endogenous development (Diochon, 1997), as well as the large body of participatory rural appraisal (PRA) and other self-mobilizing techniques (Chambers and Conway, 1991; Chambers, 1994) associated with participatory action research.

ABCD is not that new, but its innovation lies in providing a conceptual and operational framework for recognizing that communities have driven their own development since time immemorial, and that they have done so in the absence of usually well-meaning external actors. Its second major innovative aspect lies in its ability to frame and guide a structured co-creation process that fosters responsive external action. ABCD falls within the broader spectrum of community-driven development approaches that have received increasing global attention since the 1990s, particularly in the context of the rise of the sustainable development paradigm as the international development leitmotif (Guyer and Richards, 1996; Okidi et al., 2008). Drawing on Russell (2017), different perspectives and approaches to community development have been proposed (Table 1).

While there is important internal ontological coherence and conceptual congruence, ABCD is operationalized in different ways by individuals and groups around the world.[1] ABCD is sometimes facilitated by external actors, or adopted by organic collectives, networks, and groups to structure their own collective action. In line with the diversity of voices in the ABCD space, there have been considerable differences between the specific ABCD practices and related research approaches implemented by the CIFOR-ICRAF ABCD team over the past decade, despite drawing on the same sources and tools (Fuchs, 2018; Fuchs et al., 2019a,b, 2020, 2021a,b, 2022). Typically, we have used ABCD to initiate and structure engagement with communities to foster the co-design of specific socio-technical support modules, which we implemented *in response* to the

1 Some of the very active ABCD networks include ABCD Institute institutional partners around the world, including Nurture Development led by Cormac Russel, the ABCD Institute's lead partner in Europe (https://www.nurturedevelopment.org/); the Bank of IDEAS, the lead partner in Australia (http://bankofideas.com.au/); the Jeder Institute (https://www.jeder.com.au) also in Australia; and the Tamarack Institute (https://www.tamarackcommunity.ca/) in Canada. The global ABCD community also organizes under the label of 'ABCD in Action' (https://abcdinaction.org/), and is strongly represented in the International Association for Community Development (https://www.iacdglobal.org/) and its journal *Practice Insights*.

TABLE 1 Different perspectives and approaches in community development.

	Type 1	Type 2	Type 3	Type 4
Type of approach	Deficit model; medical model	Charity model	Social model; Coproduction; Externally facilitated ABCD	Fully community-driven ABCD
Localization of power and agency	Top-down	Top-down	Top-down + Bottom-up	Bottom-up
The role of the people	Everything is done *to* and *without* the people	Everything is done *for* and *without* the people	Everything done is *for* and *with* the people	Everything done is *for* and *by* the people

Source: Adapted from Russell (2017).

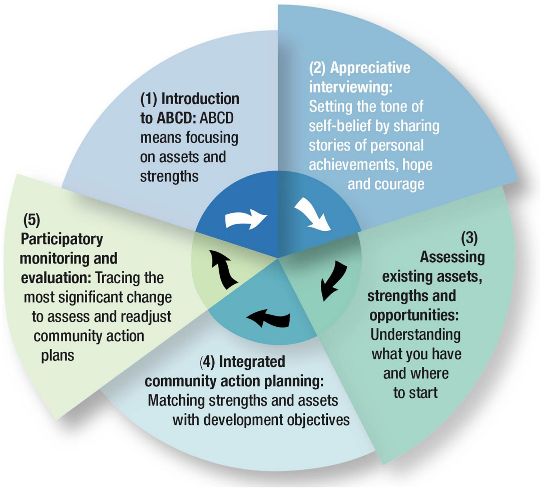

FIGURE 1
The five steps of the "ABCD practice wheel" used in "ABCD in Regreening" project. Source: adapted from Fuchs et al. (2020, pp. 35–36).

asset-based and agency-focused community action plans developed through the ABCD process. Unlike in other projects where ABCD was embedded in this broader research-in-development process, the "ABCD in Regreening" project explicitly focused on the *intrinsic* contribution that ABCD can make to supporting sustainable scaling. In terms of specific practice, the "ABCD in Regreening" project adopted a condensed and highly integrated "pure" ABCD process[2] that included 5 main steps (see Figure 1). Through these five steps, participants are encouraged to first focus on opportunities, the "glass half full," to be able to face challenges (Step 1); share stories of success to generate a sense of pride and hope

TABLE 2 The five general contribution claims for ABCD.

Category	Label	Summary description
Attitudinal changes	Asset mindset	People realize and appreciate what they have
	Sense of agency	People believe in their ability to influence their lives positively
Behavioral changes	Individual action	People decide to start with what they have and use it better, and in a more coordinated way, at an individual level
	Collective action	People come together and start with what they have collectively within their social networks to achieve joint objectives
	Strategic collaborations	People use their social networks to find solutions through strategic collaborations and partnerships with external actors

Source: Authors.

(Step 2), discover, assess, and value what they already have (Step 3); link what they have with their objectives to mobilize their assets for concrete action (Step 4); and engage in regular self-reflection and self-evaluation to strengthen their resolve and adapt their personal and community action plans (Step 5).

ABCD, as an approach, is content-neutral and does not explicitly promote specific farming practices or livelihood options. In line with this general applicability, the first objective of the "ABCD in Regreening" project was to demonstrate that "adding" an ABCD module to the Regreening Africa project in Kenya would contribute *intrinsically* to strengthening the targeted farmers' adoption and sustainable engagement in "Regreening practices." Expected effects include both general and specific intrinsic effects. Based on extensive previous action research, the three underlying ABCD principles, and the five steps of the ABCD practice wheel, we developed five *general* intrinsic contribution claims for ABCD (Table 2; Supplementary Table S1 for additional information). In addition, the

2 After identifying two core opportunities for responsive support, we carried out two technical support trainings. In the first, a subset of ABCD group members (details of group selection and sampling are presented in Section 2.2 of the paper) were invited to participate in a training in agroecological soil, water, and integrated pest management techniques that held on a Regreening Africa lead-farmer's farm and that brought together experts from research, extension, NGOs and the government in a co-learning process. The second was in small-scale business tools and record keeping, drawing on specific participatory value chain analysis and business tools used in other ABCD projects (Fuchs et al., 2019a,b).

specific intrinsic effects of implementing ABCD in the context of Regreening Africa include empowered ABCD participants seeking strategic collaboration opportunities with the Regreening Africa project and engaging with the local Regreening model farmers for co-learning and collective action. To provide robust evidence on the specific processes, sequencing, and mechanisms, the ABCD team developed a detailed theory-based contribution analysis framework, and an associated mixed-methods research design, which are published together with the results in Fuchs et al. (2024).

In the context of growing recognition of agroecology's potential role in addressing the key crises of our time (HLPE, 2019; IPCC, 2023), and a significant increase in scientific interest and investment in agroecology (Geck et al., 2023), our second objective was to more specifically evidence ABCD's role in sustainable scaling by contextualizing its conceptual and practical contribution to agroecology. This research interest was warranted given the overlap between the regenerative focus of Regreening practices, ABCD's intrinsic focus on resource efficiency, and its overarching focus on assets and agency rather than deficits and needs.

Agroecology is a polysemic concept with various definitions that incorporates ecological and social considerations in the pursuit of improved interactions among plants, animals, humans, and the environment, with a focus on a sustainable and equitable food system. Based on the historical principles of agroecology defined by Alteri (1995), and further inspired by Gliessman's (2015) five levels of agroecological transitions and others, FAO (2018) proposed a consolidated set of 10 elements of agroecology. These elements combine the five ecology-centered elements of efficiency, recycling, diversity, synergies, and resilience, with five more human-centered elements, namely responsible governance, circular and solidarity economy, human and social values, and culture and food traditions. Barrios et al. (2020) developed this framework by drawing on existing analyses that have advanced agroecology as a science, a practice, and a social movement (Alteri, 1995; Gliessman, 2015; Tittonell, 2014; Tomich et al., 2011; Wezel et al., 2014), as well as efforts to address global sustainability challenges (Springmann et al., 2018; Steffen et al., 2015). In 2019, the High-Level Panel of Experts on Food Security and Nutrition (HLPE), the science-policy interface of the UN Committee on World Food Security (CFS), proposed an alternative list of 13 agroecological principles (HLPE, 2019). The principles, whose essence is succinctly summarized in Sinclair et al. (2019), were derived from combining and reformulating principles from three main sources, namely CIDSE (Coopération Internationale pour le Développement et la Solidarité) (2018), FAO (2018), and Nicholls et al. (2016). With the objective to "produce a minimum, non-repetitive but comprehensive set of agroecological principles" (HLPE, 2019, p. 39), the 13 principles are organized around three operational principles, that the HLPE says underpin sustainable food systems (Table 3). While individual principles have been assigned to the operational principle to which they most clearly contribute, interlinkages between the categories have been recognized.

While ABCD is a content-neutral engagement "vehicle," its focus on assets and their efficient and sustainable use aligns with CFS HLPE (2019) principles 1 to 7, which fall under the operational principles of resource efficiency and resilience. At the same time, its focus on agency, which includes considerations related to empowerment, inclusion, and participation, pairs particularly well with considerations subsumed under the operational principle of social equity. There are numerous specific ways in which the ABCD principles and practice can be mapped onto the 13 principles (Supplementary Table S2). Beyond this conceptual congruence, ABCD fundamentally provides a way to *enact* principle 8 on co-creation of knowledge (and action) and to ensure principle 13 on participation (related to agency).

In this paper, we focus on the importance of process in international development in general, and in large-scale land restoration projects in particular. For Regreening Africa, the primary interest of this collaborative research project was to identify and test sustainable scaling models to address anticipated and experienced challenges in achieving the project's ambitious targets in its intensification sites in western Kenya. While we developed a realist contribution analysis research design based on an actor-centered theory of change to identify the specific mechanisms underlying the contribution of ABCD to the identified attitudinal and behavioral changes (details in Fuchs et al., 2024), this paper focuses on the key outcome targets of the "ABCD in Regreening" project. The primary research question was therefore whether the adoption of an asset-based and agency-focused engagement approach—with its emphasis on self-assessment, self-realization, self-actualization, and self-evaluation—made an *intrinsic* positive contribution to impact of Regreening Africa on livelihoods and landscapes. This paper also provides insights into the methodical process we followed to first "define what matters," and then develop a specific tool that allowed to "measure what matters," and finally to "produce evidence on what matters" in response to this question. The process and results are presented, and their implications are discussed in the following sections.

TABLE 3 The 13 HLPE agroecological principles and their nesting under operational principles.

Improve resource efficiency		Strengthen resilience				
Principle 1	Principle 2	Principle 3	Principle 4	Principle 5	Principle 6	Principle 7
Recycling	Input reduction	Soil health	Animal health	Biodiversity	Synergy	Economic diversification
Secure social equity						
Principle 8	Principle 9	Principle 10	Principle 11	Principle 12	Principle 13	
Co-creation of knowledge	Social values and diets	Fairness	Connectivity	Land and NR governance	Participation	

Source: HLPE (2019).

2 Methodology

2.1 Study location and background

As mentioned, the ABCD in Regreening project was implemented in the context of the wider Regreening Africa project, which aimed to restore large areas of land in eight African countries, including Senegal, Mali, Niger, and Ghana in West Africa, and Rwanda, Kenya, Somalia, and Ethiopia in East Africa from 2017 to 2023. The ABCD in Regreening project used a five-pronged ABCD approach to support sustainable individual and collective behavior change in support of the widespread adoption of and engagement in so-called Regreening practices. These include on-and off-farm practices that can be ranged under agroforestry, soil health, pasture management, household resource efficiency measures, alongside value chain development, and financial inclusion measures (see Table 4 for more details).

Therefore, this study was conducted in the Regreening Africa “intervention” site in Homa Bay County in the wider western region of Kenya. Homa Bay County, located between latitudes 0° 15’S and 0° 52’S and longitudes 34°E and 35°E (Figure 2), covers an area of 4,267 km^2 and comprises eight sub-counties (Regreening Africa, 2018).

As mentioned above, Regreening Africa aimed to directly engage with a total of 10,000 households, 3,500 of which were located in Homa Bay County. Through an in-depth inventory and assessment effort, Regreening Africa identified intervention and comparison sub-locations, which were also referred to as intensification and scale-out sites, respectively. Regreening Africa engaged households in both intensification and scale-out sub-locations, albeit at different points in the project implementation cycle, and with different activities (Regreening Africa, 2018).

2.2 Sampling framework

The overall targeting approach of “ABCD in Regreening” built on Regreening Africa’s territorial intervention logic, which structured both the selection of ABCD project participants and the sampling of survey respondents. The study relied on Regreening Africa’s distinction between so-called “intensification” and “scale-out” sub-locations in the Suba North and Suba South sub-counties.

TABLE 4 The nine key “Regreening practices” implemented in Kenya and their inductive categorization.

Category	Regreening practice
Agroforestry	(1) FMNR
	(2) Fruit tree farming
	(3) On-farm integration of indigenous trees
	(4) Enrichment planting
Soil health	(5) Soil and water conservation
Pasture management	(6) Reseeding with adaptable grass species
Household resource efficiency	(7) Energy saving options
Value chains	(8) Value chain development
Financial inclusion	(9) Financial inclusion

Source: Authors drawing on Odhiambo (2020).

We used a multi-stage sampling design. First, we defined three clusters within the two sub-counties, namely Lambwe, Ruma-Kaksingri East, and Kaksingri West (Figure 2). Each cluster contained several sub-locations, which were defined as so-called cluster cells. Second, based on Regreening Africa’s sampling, we randomly designated one Regreening “intensification” sub-locations as an ABCD cluster cell, and another Regreening “intensification” as a Pure Regreening cell within each cluster. The selection of both the ABCD and the Regreening cells among the intensification sub-locations was to ensure that all had been involved with Regreening Africa, while only those in ABCD cells would also be involved with the ABCD team. This would allow us to compare the treatment effects between those who had participated in the “ABCD in Regreening” project and those who did not. Third, we randomly designated one “scale-out” sub-location as a Comparison cell within each cluster. These had previously served as controls in Regreening Africa. In total, we designated three ABCD cells, three pure Regreening cells, and three Comparison cells, one in each of the three clusters.

Following Fuchs et al. (2021b), we identified 30 ABCD groups from within the ABCD cells using a structured and purposive selection process. The approach allows identifying community groups that are contextually suitable for projects implemented by external actors. The tool is structured around two attributes: a group wellbeing index (material assets), and a group capacity and agency index (social capital). Each index consists of seven indicators. We administered the tool through a questionnaire containing 14 questions, each of which was linked to a pre-set 5-point Likert-type items. The survey forms were distributed during community entry after introducing the proposed project during local *barazas* held by the respective local authorities. Registered local community groups within the selected sub-locations, including self-help, women, and youth were invited and mobilized to collect and complete the survey form. Submissions were made either directly or through the local authorities.

We received completed questionnaires from 163 community groups in the nine pre-identified cells. After reviewing all the submissions, we used statistical analysis to classify all complete and legitimate submissions in the different group types (Type 1 through Type 4). Following the purposive selection method, we then randomly selected groups falling into different group types within each individual cluster cell to identify the 30 ABCD groups, 10 from each cell. We used the same approach to identify 15 groups from the Regreening cells, and 15 from the Comparison cells. We aimed to keep the distribution of group types constant in each sample.[3] Finally, from the 60 groups, we identified 10 households per group within the respective cluster cells using stratified randomized sampling to arrive at a total sample size of 600 households.

3 To further investigate the hypothesis that emerged from previous research see (Fuchs et al., 2021a,b) that types 1 and 3 are more likely to perform well, we targeted an equal distribution of group types during ABCD group selection. However, ground-proofing of the recruited groups led to a slightly skewed distribution, and more type 3 groups (28%) than type 4 (25%), type 1 (23%), or type 2 groups (23%). Similarly, while we targeted a similar group type distribution within each sample, and ideally within each cluster, but ended up with considerable differences in group type composition between the samples as indicted in Table 10.

10.3389/fsufs.2024.1449615

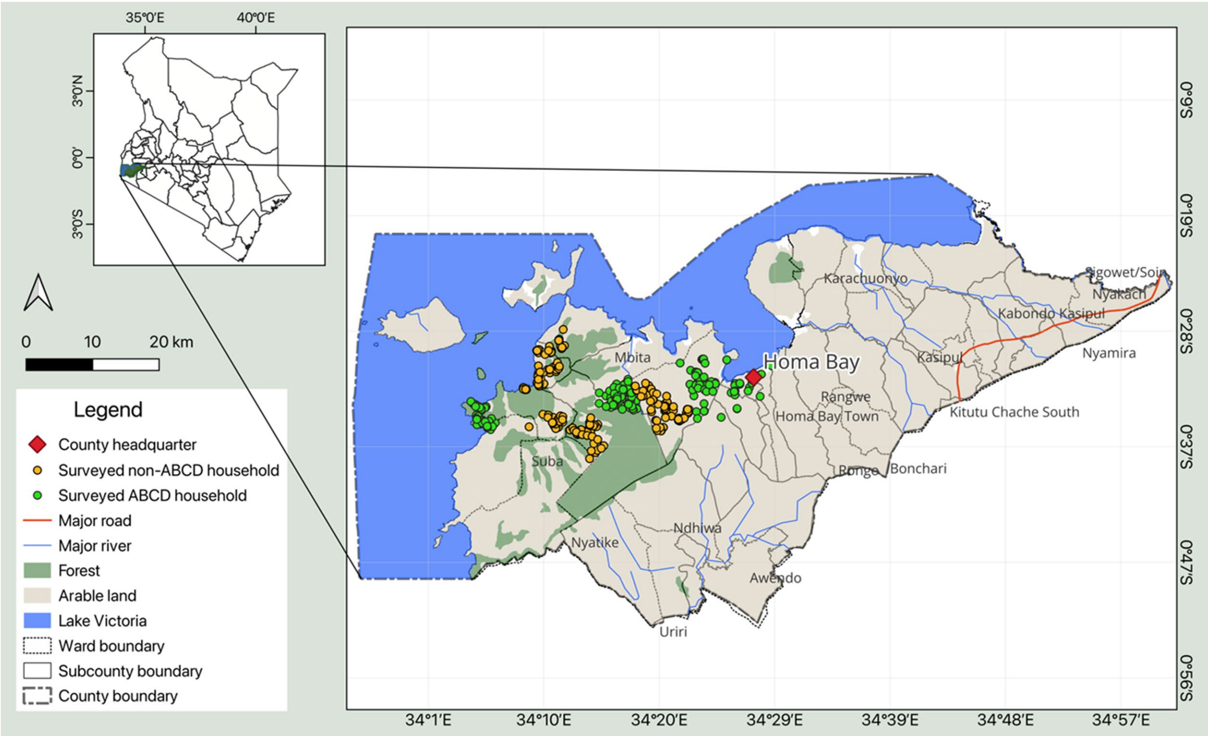

FIGURE 2
ABCD and non-ABCD households sampled in Homa Bay County in western Kenya. Source: Authors.

2.3 Data collection

We conducted baseline and endline surveys using a pre-tested questionnaire in Kobo Toolbox to capture demographic and farm system characteristics, as well as involvement with Regreening Africa. While we rolled out the "ABCD in Regreening" project to all members of the 30 ABCD groups, which included approximately 750 individuals, only 300 of them were included in the survey. The endline survey was conducted in September 2023 using the same questionnaire as the baseline, with 524 of the original 600 respondents re-interviewed. The attrition rate was 12.67%, and 48 outliers were omitted to ensure data accuracy. Of the final total sample of 476 respondents, 248 belonged to the ABCD sample, and 228 to the non-ABCD sample, with 67 being Regreening, and 161 being Comparison households.

2.4 Analytical framework

2.4.1 Introduction to the conceptual and empirical framework

As discussed, the investigation of the interaction of ABCD with agroecology was embedded in the broader ABCD contribution analysis (Fuchs et al., 2024). As part of the overall research design, and to ensure that the research approach and methods were indeed "measuring what matters" (Geck et al., 2023; Lamanna et al., 2024), we engaged in and documented an in-depth reflection process that interrogated and confirmed the overall research framing and ontology, the conceptual congruence between core project and analysis activities and objectives, and the specific and comprehensive research design. Since the main objective of the "ABCD in Regreening" project was to support the outcomes of the Regreening Africa project, we first analyzed the nature and assessment methods associated with Regreening Africa, as well as the assessment methods associated with agroecology, and then looked at the overlaps between Regreening and agroecological practices, as well as between Regreening, agroecology, and ABCD altogether.

We adopted this methodical and stepwise approach to analyzing the three core concepts and assessment frameworks to first ensure that an agroecological framing would be applicable to the goals of the Regreening Africa project that the "ABCD in Regreening" project aimed to strengthen. Consequently, the first aim was to clearly "define what matters." In addition, this approach aimed to lead to the adoption of a relevant assessment framework that would allow us to assess the targeted behavioral changes among the "ABCD in Regreening" project participants in a relevant manner. The second aim hence was to develop an assessment tool that would allow us to "measure what matters," and the third was to develop an empirical framework for data analysis to "produce evidence on what matters."

2.4.2 Defining what matters: what are Regreening and agroecology practices and how are they assessed?

As a first step, we examined how Regreening practices were defined and assessed. Based on the Regreening Africa country implementation plan for Kenya (Regreening Africa, 2018), Regreening Africa combined biophysical and socio-economic assessments to develop combinations of restoration options that deemed appropriate at the respective local level.

TABLE 5 Focus on the F-ACT criteria for which the strongest positive effect is projected.

System component	Agroecological principle	Question	Consideration (ABCD promotes)
Household	Economic diversification (7)	Does your farm activity provide you with sufficient income to meet your goals and invest in further development?	Households are encouraged to use existing skills and assets more efficiently in various income-generating activities; and intrinsically focuses on diversification.
	Co-creation of knowledge (8)	Do you keep farm records?	Self-assessment, self realization, self-actualization, and self-evaluation—including by promoting on-farm record keeping with Commodity and Integrated Household Leaky Bucket.
	Fairness (10)	Do men and women have equal power in decision making processes relating to farm management?	Intra-household relationship improvement in line with "everyone has gifts" and "start with what you have" principles, as well as the Integrated Household Leaky Bucket.
Community	Economic diversification (7)	Are you a member of any farmers' organizations for collective sales of produce?	People value each other, identify joint interests, and act collectively; farmer organizations, including cooperatives, are core to these undertakings
	Co-creation of knowledge (8)	Are you involved in any platforms for knowledge sharing or co-creation?	Mutual respect and recognition in line with the "relationships build community" principle and social capital and network assessment, which foster planning for collective action and strategic collaborations.
	Participation (13)	How much do you participate in collective farming activities or landscape management?	Core principles focus on relationship building, strategic partnerships, and the development of joint visions for collective action for the individual and communal good.

Source: Authors.

Koech et al. (2020) note that "[p]roject learning and evidence have helped refine and diversify the recommended options, including FMNR and enrichment planting with multipurpose timber and non-timber trees; soil and water conservation with agroforestry trees and grasses (contour bunding, sand dune stabilization, halfmoon catchments and zaï pits); exclosures; *in-situ* grafting and direct sowing; and fire management" (p. 4). The Regreening Africa Baseline Report provided additional qualitative research results on the identification and prioritization of tree-based value chains, particularly timber and fuelwood. Three value chains were prioritized for Kenya based on a gender-differentiated preference assessment combined with other considerations such as income generation potential, as well as market access and demand: Honey, mango and pawpaw. Key challenges for these value chains were identified as being (a) limited access to quality germplasm (mango and pawpaw), (b) inadequate harvesting and post-harvest handling skills, (c) equipment, and (d) financial management skills (Hughes et al., 2020).

While the restoration options presented focused primarily on land-based practices, the Regreening Africa team also included broader socio-economic enhancement practices as well. These include further development of the selected value chains, as well as a focus on energy saving options and financial inclusion. According to a presentation given by World Vision Kenya in November 2020 (Odhiambo, 2020), the key Regreening practices implemented in the direct intervention sites in Kenya included both on-farm and/or environmental, as well as on off-farm concerns (Table 4).

Although the Regreening team initially developed a household adoption survey to monitor its two key performance indicators, the Regreening team soon focused more specifically on its Regreening Africa Index (RAI), a multi-dimensional index that combines an analysis of the extent, intensity, and diversity of practices with intra-household equity. The RAI is modeled on the Agroforestry Adoption Index, whose measurement approach is similar to that underlying the Multidimensional Poverty Index (MPI) and the Women's Empowerment in Agriculture Index (WEAI; Hughes et al., 2020).

In the second step, we specifically examined ways to assess agroecology and compared existing frameworks for their suitability to our context. Using similar information sources, Geck et al. (2023) recently inventoried 11 assessment frameworks and methodologies, which were developed by different actors, based on different conceptual frameworks, and differed in their focus in terms of scale.

In a third step, we used Biovision's ACT tool (Biovision Foundation, n.d.) to explore an initial congruence between Regreening Africa and agroecology. Based on the FAO 10 Elements and Gliessman's five levels, ACT assesses how agroecological a given project, policy or initiative is; and/or the extent to which these projects are likely to deepen the level of agroecological integration of targeted households, communities, or landscapes. In order to analyze the Regreening practices implemented in the intensification sites of the Regreening Africa project in Kenya, we used the nine key Regreening practices introduced in Table 4 as a basis for evaluation, rather than conducting a more in-depth secondary data analysis and/or collecting primary data. To address the indicators ranged under the food system-focused elements, we also considered additional complementary information on Regreening communication channels and implementation processes [also presented in Odhiambo (2020)]. The results of this initial rapid assessment showed a positive engagement between Regreening practices and almost all of the agroecosystem-focused elements, especially in recycling (83%) and synergies (75%), but also efficiency (57%), diversity (56%), and regulation and balance (50%). Looking at the food system-focused elements, the results for only two exceeded the 50% mark, namely human and social values (67%) and culture and food traditions (50%). Responsible governance, on the other hand, registered no engagement. Despite methodological shortcomings, such as the use of the summary presentation given by the lead project manager rather than on the project proposal and document as a data source, and despite noting several critical observations about the tool itself,[4] we interpreted the positive summary performance score[5] of 49% as sufficient grounds to confirm beyond reasonable doubt the relevance of agroecology concepts to the activities and outcomes of the Regreening Africa project.

2.4.3 Measuring what matters: developing an agroecology-based tool to assess the "ABCD in Regreening" contribution to Regreening Africa objectives

While the main project purpose of the ABCD in Regreening project was based on the objectives of the Regreening project and was defined as "improved adoption of context-specific sustainable and agroecological land restoration options," after confirming sufficient conceptual overlap between Regreening and agroecology, we explored the benefits of using the F-ACT tool to actually monitor changes among project participants. F-ACT is an adaptation of the ACT tool that uses the HLPE principles as conceptual basis, captures behavioral changes at the farm-and household level, and focuses on collecting data on respondents' actual knowledge and practices within their farms and households. We specifically analyzed the suitability of F-ACT to ensure that it can actually measure what matters. According to the developers, the purpose of the tool was to "to assess the agroecological status of a farm in order to highlight how a farmer could further develop their farm" (Biovision Foundation, 2020).

The F-ACT tool consists of a questionnaire with several questions for each of the 13 principles, with pre-set answers corresponding to a 4-level Likert scale. The tool includes 58 criteria or indicators. Analytically, F-ACT proposes aggregated data outputs and interpretations at two levels (on a scale from zero to three). First, the "Agroecology Principle Indicators" overview shows the level of engagement of a respondent with the 13 individual agroecology principles. Second, the so-called "Agroecosystem Component Indicators" overview, which calculates the depth of agroecological integration in the different identified system components. The latter are divided into nine on-farm and three off-farm agroecosystem components. According to the authors, the bar graphs illustrating the data from these two levels, together with the contextualization questions on goals and challenges, are intended to inspire respondents to foster practical action planning. Mathematically, both aggregate indicators can be defined for the F-ACT tool as:

$$Score_{ijt}^{FACT} = N^{-1}\sum_{i=1}^{13}\sum_{j=1}^{n_i} S_{ijt} \qquad (1)$$

where S_{ijt} is the household's score for question j in outcome category (agroecological principle or system component) i at time t, n_i is the number of questions gauging performance in outcome category i.

To assess compatibility, we first reviewed all 58 criteria and mapped the expected *intrinsic* effects of taking an ABCD approach on a 3-point Likert scale to confirm a basic match between the expected project outcomes and the outcomes captured by F-ACT. At the same time, we also looked for criteria that might not be applicable in the Kenyan context and identified five that could be excluded from the analysis.[6] We projected that 46 (79%) of the 58 criteria were likely to

4 Some negative aspects include the lacking clarity about the boundaries of some criteria leading to overlaps; grossly simplified answer options (yes/no; no levelling of answers); absence of information translated in the absence of positive observations (does not allow to discount indicators that might not be relevant in a given context); amalgamation of household and system level observations; deliberate interpretation of observed situations or behaviour as project effects equals farmers' practice and wider systemic changes being treated as a black box with little history and agency; considers project's intention/mission rather than actual implementation (and if so, by whom, how many, which surface area?).

5 The summary score is not included in the original tool, but was developed by us for the F-ACT tool later. The summary score is a simple average score of all individual Element percentages.

6 Despite the F-ACT tool having been developed and tested in Kenya, some questions and pre-set answer options are hardly pertinent in the Kenyan context. These include: (1) Since most of the regular electricity in the grid is renewable (geothermal, water), the focus on 'switching' to renewable energy sources is not necessarily pertinent in terms of an environmental sustainability argument. Although some value solar for self-sufficiency reasons, households might rather aspire to being connected to the grid than deliberately avoiding the grid to focus on self-produced renewable energy alone. (2) The negative evaluation of zero-grazing in relation to animal health is not contextually pertinent. Zero-grazing is often preferred option to allow for mixed farming and is rendered animal-friendly and sustainable through cut-and-carry etc. (3) Organic markets are not well developed in Kenya, especially in rural areas. Farmers aspiring to target organic markets is hence rather unlikely in our context. If they do, it is typically for export rather than to feed the local economy. (4) Farmers sell much of their non-cereal produce in local markets, and 'going local' is typically neither part of farmers' aspirations, nor progress towards agroecology, but rather a status quo. (5) While land tenure and ownership are fundamental, this is a rather static component that is not likely to change. It is hence disputable whether it should be captured in a tool geared towards monitoring changes observed over time.

TABLE 6 Overview of ABCD-centered questions and related considerations to complement F-ACT tool.

System component	Agroecological principle	Question	Consideration (ABCD promotes)
Value chains	Co-creation of knowledge (8)	How do you access and share information about market prices?	Active identification of information channels for market prices and information sharing
	Social values & diets (9)	Do you consider the potential benefits of buyers who might buy your produce before choosing where to sell it?	Safeguarding of produce to improve selected people's access to nutritional foods.
	Fairness (10)	Are you able to access different markets of your choice in search of good prices?	Fair and equal access to markets and/or fair prices for own produce.
	Participation (13)	Do you actively work with other members of your farmer and/or informal producer group to improve your economic opportunities?	Participation in a farmer group and/or informal producer group to jointly identify and pursue opportunities in the local economy
Household	Social values & diets (9)	Who is responsible for the wellbeing and advancement of your household?	Positive self-valuation, self-efficacy, autonomy, and belief in own agency and capabilities.
	Participation (13)	Do you actively participate in a group savings and loaning group?	Membership and/or active participation in joint savings and loaning schemes.
Community	Social values & diets (9)	How well do you know, appreciate, and work with your neighbors, and how well do they know, appreciate, and work with you?	Enhanced sense of people's identities, interests and preferences (IIP).
	Participation (13)	Do you, individually or collectively with other members from your community group, collaborate with external actors (i.e., extension service, NGOs, government funding schemes etc.)?	Engagement in strategic collaboration with external actors from whom support can be leveraged.

While the first three additions under the "value chains" component easily suit their localization, the alignment of the other additional criteria with the existing framework is defendable, but less obvious. Source: Authors.

be positively influenced, of which 22 (38%) directly. In terms of principles, we projected the strongest effects (defined as the total percentage of direct positive effect predicted by the original F-ACT per principle or system component being equal to or greater than 50%; see in Table 7) in co-creation (100%), economic diversification (71%), connectivity (50%), and participation (50%), and for the trees (100%), as well as for the household (60%), community (57%), and value chain (50%) system components. Looking at individual criteria, we projected particularly strong effects in six criteria (Table 8).

In a second step, we considered whether the tool itself had gaps that could be addressed to avoid under-reporting of the expected effects of taking an ABCD approach. First, we found that the tool was clearly biased towards on-farm and resource efficiency and (technical) resilience strengthening. Despite proposing a few relevant criteria within the "lower right" where human-centered on-farm and off-farm system components meet with social equity principles (Table 7), explicit questions assessing social-cultural and socio-economic dynamics that contribute to deepening the level of agroecological integration remained rather few. In detail, we found that of the 58 proposed criteria, 44 criteria (76%) fell under the operational principles of resource efficiency and resilience, while only 14 (24%) fell under the operational principle of social equity; 47 criteria (81%) addressed on-farm system components, and only 11 (19%) addressed off-farm components; 37 criteria (64%) were allocated in the "upper left" section of the table and aligned with principles 1 to 6, and exclusively related to on-farm system components; 7 criteria (12%) fell under principle 7, the only principle that addressed both on-and off-farm system components; and 14 criteria (24%) fell within the "lower right" section of the Social equity operational principle, of which only 11 (19%) related to off-farm livelihood components.

In a third step, we adapted the F-ACT tool was to include additional criteria relevant to the Kenyan context, creating the F-ACT+ tool, which better captures the social and economic dynamics targeted by the ABCD approach Table 7. The F-ACT+ aggregate principle and system component scores can be defined as:

$$Score_{ijt}^{FACT+} = N^{-1}\sum_{i=1}^{13}\left(\sum_{j=1}^{n_i} S_{ijt} + \sum_{j=1}^{8} P_{ijt}\right) \quad (2)$$

TABLE 7 Projected areas that taking an ABCD approach is likely to influence within the F-ACT+ matrix.

	1	2	3	4	5	6	7	8	9	10	11	12	13
Soil (1)													
Water (2)													
Crops (3)													
Livestock (4)			*										
Trees (5)													
Pests (6)													
Energy (7)	°												
Household (8)												^	
Workers (9)													
Community (10)											‡		
Value chain (11)							†						
Policy (12)													

The 13 Principles of Agroecology are listed in the columns, and the 12 system components in the lines.
Green denotes a likely direct positive effect; yellow a likely indirect positive effect; blue likely no effect; dark green the projected strongest positive effect among original F-ACT criteria, and marron the new ABCD criteria with likely direct positive effects as well.
Symbols were placed in the criteria that are not applicable in the western Kenyan context: ° Switching to renewable energy. * Negative evaluation of zero-grazing. † Accessing organic markets. ‡ Targeting local markets. ^Land tenure change.
Source: Authors.

where P_{ijt} is a household score in an additional question deemed necessary to the original F-ACT tool after the adjustment.

In developing these additional criteria, we drew on prior work on empowerment and agency, including the project-level adaptation of the Women in Agriculture Index (pro-WEIA), and the distinction between intrinsic, instrumental, and collective agency (Malapit et al., 2019), which aligns neatly with our "sense of agency," "individual action," and "collective action" outcomes. Our indicators were also inspired by practical and context-specific insights from our more than 10 years of experience, and focus on assessing the crucial social-cultural and socio-economic dynamics targeted by ABCD, which were under-represented in the original F-ACT tool. Because of their clear alignment with agroecology, they can also be positioned as likely contributors to deepening agroecological integration (Table 6; the full details can be found in Supplementary Table S3).

Increasing the number of criteria by eight (see maroon additions Table 7) to 66 made it possible to balance the proportion of criteria located under the social equity operational principle from 24 to 33%. Looking at the sub-systems, the balance shifted from 19 to 29% of off-farm criteria. Based on this adjustment, we projected direct positive effects on 30 (45%) and indirect positive effects on 24 (36%) criteria, for a total positive effect on 54 (82%) of the captured criteria. In F-ACT+, we expected the strongest effects of the project in six principles and included co-creation (100%), participation (80%), economic diversification (71%), social values and diets (60%), fairness (50%), connectivity (50%). At the system component level, we expect the strongest effects in trees (100%), as well as value chain (83%), household (71%), and community (67%).

As mentioned above, we also eliminated five specific criteria that were not applicable in the western Kenyan context. This adaptation resulted in the F-ACT Minus 5 and F-ACT+ Minus 5 variants of the original F-ACT tool, and are defined as follows:

$$Score_{ijt}^{FACT\ Minus\,5} = N^{-1}\sum_{i=1}^{13}\left(\sum_{j=1}^{n_i} S_{ijt} - \sum_{j=1}^{5} M_{ijt}\right) \quad (3)$$

$$Score_{ijt}^{FACT+Minus\,5} = N^{-1}\sum_{i=1}^{13}\left(\sum_{j=1}^{n_i} S_{ijt} + \sum_{j=1}^{8} P_{ijt} - \sum_{j=1}^{5} M_{ijt}\right) \quad (4)$$

where M_{ijt} represent a household score in a question deemed irrelevant during the localization process.

Excluding the five inapplicable criteria, the percentage of expected positive change increased to 89%, including 49% for expected direct positive change. In the adapted version of the tool, the number of principles we predicted to be most positively affected increased to seven, and included governance (50%), with some values increasing. At the system component level, the number remained at four, with values increasing for the three off-farm components.

2.4.4 Producing evidence On what matters: empirical framework

To estimate the evolution of the ABCD group in terms of agroecological integration (1), system components (2), and overall agroecology performance (3) and hence the so-called average treatment effect on the treated (ATT), we used the doubly robust difference-in-differences (DRDID) estimator proposed by Sant'Anna and Zhao (2020). Rather than comparing the performance of different samples in absolute terms, the DRDID approach compares the degree of improvement within each sample to the degree of improvement in another sample. It thus provides relative comparisons that acknowledge differences in initial performance, and focus on the trajectories and trends rather than absolute values. The DRDID approach is attractive for a number of reasons. First, because our panel data have only two periods namely baseline (pre-treatment period, $t=0$) and endline (post-treatment period, $t=1$), it is impossible to "test" whether or not the parallel trends assumption holds—an identification strategy for the ATT. In essence, this assumption requires that, in the absence of the treatment, both the ABCD and non-ABCD groups would have experienced a similar evolutionary trend (or simply, average variance over time). However, it is well known that conditional parallel trends can be recovered through the inclusion of the pre-treatment covariates (Abadie, 2005; Heckman et al., 1997). Second, the ATT from the DRDID is consistent provided that either the propensity score or the outcome model is correctly specified, but not necessarily both. Third, under panel settings, the DRDID is locally efficient for the semiparametric bound (Sant'Anna and Zhao, 2020). Finally, the approach is easy to implement, and its parametric nature evades the "curse of dimensionality."

Suppose our treatment assignment mechanism is given by a binary treatment variable D so that:

$$D_{it} = \begin{cases} 1, \textit{if a household i participates in ABCD program at time t} \\ 0, \textit{otherwise if a household i does not participate in ABCD program at time t} \end{cases} \quad (5)$$

Let Y_{ijt} be household i's score on outcome category j (which can be either agroecological integration, system components or overall agroecology performance) at time t, $\pi(X) = \Lambda(X'\varphi)$ to represent the true unknown propensity score model, and $m_{d,\Delta}$ be the true unknown outcome regression $m_{d,\Delta} \equiv m_{d1}(X) - m_{d0}(X) \equiv \mathbb{E}[Y_t | D = d, X = x]$. Following Sant'Anna and Zhao (2020) and Callaway and Sant'Anna (2021), the DRDID for panel data was estimable in three steps. In the initial step, we estimated the probability of participating in ABCD conditional on covariates using an inverse probability tilting (IPW) estimator proposed by Graham et al. (2012) as:

$$\hat{\varphi} = \underset{\varphi \in \Gamma}{\arg\max}\, \mathbb{E}_n \left[DX'\varphi - (1-D)\exp(X'\varphi) \right] \quad (6)$$

where $\mathbb{E}[\cdot]$ is the expectations operator, $\hat{\varphi}$ is the IPW estimate of the pseudo-true φ, Γ is the parameter space, and X is a set of pre-treatment covariates that are thought of influencing the probability of exposure to the ABCD treatment. A description of the covariates used in the IPW models is outlined in Table 6.

Next, we estimated an outcome regression by weighted least squares approach, where we imputed the potential outcome evolution for the ABCD group with a regression based only on the covariates of the control group (either non-ABCD, or its subsets: Comparison or Regreening) following Heckman et al. (1997):

$$\hat{\beta}_{0,\Delta} = \underset{\beta \in \Theta}{\arg\min}\, \mathbb{E}_n \left[\frac{\Lambda\left(X'\hat{\varphi}\right)}{1-\Lambda\left(X'\hat{\varphi}\right)} \left((Y_1 - Y_0) - X'\beta \right)^2 \middle| D = 0 \right] \quad (7)$$

where $\hat{\beta}_{0,\Delta}$ is the weighted least squares estimator of the pseudo-true $\beta_{0,\Delta}$, Θ is the parameter space, $\Lambda(X'\varphi)$ follows a logistic specification for the nuisance function, hence $\frac{\exp(X'\varphi)}{1+\exp(X'\varphi)}$, Y_1 represents the outcome for a household in the treatment group at post-treatment period, and Y_0 is the outcome for the same household at the baseline period.

Finally, plugging φ and $\hat{\beta}_{0,\Delta}$ into the Equation 8, we obtained the ATT, ϑ, via the DRDID (Sant'Anna and Zhao, 2020) as:

$$\vartheta = \mathbb{E}\left[\left(\hat{r}_1(D) - \hat{r}_0\left(D, X; \hat{\varphi}\right) \right) \left(\Delta Y - m_{0,\Delta}\left(X; \hat{\beta}_{0,\Delta} \right) \right) \right] \quad (8)$$

where $\hat{r}_1(D) = \frac{D}{\mathbb{E}_n[D]}$, $\hat{r}_0(D, X, \varphi) = \left(\frac{\left[\frac{\pi(X;\varphi)(1-D)}{1-\pi(X;\varphi)} \right]}{\mathbb{E}_n \left[\frac{\pi(X;\varphi)(1-D)}{1-\pi(X;\varphi)} \right]} \right)$,

$\Delta Y = Y_1 - Y_0$, and $m_{0,\Delta}(X; \beta_{0,1}) \equiv m_{0,\Delta}(X'\beta_{0,\Delta})$.

Thus, the DRDID estimand becomes:

$$\vartheta = \mathbb{E}\left[\left(\frac{D}{\mathbb{E}_n[D]} - \left(\frac{\left[\frac{\pi(X;\varphi)(1-D)}{1-\pi(X;\varphi)} \right]}{\mathbb{E}_n \left[\frac{\pi(X;\varphi)(1-D)}{1-\pi(X;\varphi)} \right]} \right) \right) \left(\Delta Y - m_{0,\Delta}\left(X; \hat{\beta}_{0,\Delta} \right) \right) \right]$$

All analyses were performed in R (R Core Team, 2023) and Stata version 17.

3 Results

3.1 Descriptive statistics

The demographic and socio-economic characteristics (Table 8) of the ABCD and the non-ABCD samples were similar, but masked important within-sample differences between respondents from the different clusters, with land size, crop diversity, and the importance of farming being significantly higher in the Ruma Kaksigiri East cluster than in the others. Overall, however, the respondents had an average age of 44–45 years. Just over a quarter of the households were headed by men, with an average household size of about 7 people. The main income-generating activity of the respondents was farming. On average, a household was food self-sufficient for 6 months in a typical year. Notable differences include the size of land owned and farmed, both of which were significantly higher among non-ABCD households. One-third of the ABCD sample fell into Group Type 4 characterization, which was significantly higher than their proportion in the non-ABCD sample. While prior exposure to Regreening Africa was significantly higher among the ABCD sample, this was not as significant as expected.[7]

7 According to our sampling strategy that directly drew on Regreening Africa's sampling strategy, all ABCD households were sampled from Regreening 'intensification' sub-locations, and the Regreening households were also

TABLE 8 Socio-demographic characteristics of ABCD and non-ABCD households.

Variable	Description	Pooled	ABCD (a)	Non-ABCD (b)	Test of difference (a)–(b)	
		Mean (SD)	Mean (SD)	Mean (SD)	Diff.	*t*-test
Continuous variables						
Age (years)	Age of the household head	44.590 (13.495)	43.968 (13.835)	45.268 (13.112)	−1.300	−1.052
Household size (count)	Number of individuals in the household	6.765 (2.780)	6.657 (3.070)	6.881 (2.428)	−0.224	−0.888
Land owned (acres)	Land owned by the household	0.942 (1.831)	0.536 (1.504)	1.382 (2.045)	−0.845	−5.103***
Land farmed (acres)	Land under agricultural activities	0.630 (1.221)	0.406 (1.151)	0.873 (1.252)	−0.466	−4.235***
Food sufficiency months (count)	Number of months in a typical year when the household has access to sufficient food	6.118 (3.152)	6.266 (3.287)	5.956 (2.997)	0.310	1.072
Categorical variables		Proportions				χ^2 test
Gender	Respondent is a male (%)	28.2 (45.0)	27.4 (44.7)	28.9 (45.5)	−1.5	−0.137
Prior exposure	A household member has ever been exposed to Regreening activities (%)	39.5 (48.9)	43.1 (49.6)	35.5 (48.0)	7.6	2.886*
Group-type§	Type 1: Group has high WB and high CA (%)	26.5	29.4	23.2	5.2	3.174
	Type 2: Group has high WB and low CA (%)	25.6	19.8	32.0	−12.2	−4.721
	Type 3: Group has low WB and high CA (%)	22.9	18.1	28.1	−10.0	−3.311
	Type 4: Group has low WB and low CA (%)	25.0	32.7	16.7	16.0	15.538***
Main income activity§	Farming (%)	73.3	66.5	80.7	−14.0	−1.034
	Business (%)	21.2	25.4	16.7	8.7	6.188*
	Salaried (%)	1.7	2.0	1.3	0.7	0.500
	Other (%)	3.8	6.0	1.3	4.7	8.000**
N		476	248	228		

*, **, and *** denote statistical significance at the 10, 5, and 1% levels, respectively. § denotes variables for which p values were adjusted by Bonferroni method. Values in parentheses are standard deviations. WB, Wellbeing; CA, Capacity and Agency. Source: Survey data (2023).

3.2 Degree of agroecological integration and system components scores

There were clear differences between baseline and endline performance in agroecological integration and components addressed in the overall sample (see Supplementary Figure S1). Comparing the results from the different tool variants, the principles, systems and overall agroecology scores of the F-ACT and F-ACT+ tools were higher than those of their variants from which five performance criteria were excluded. This trend was particularly evident in the baseline data. Across the sample, F-ACT+ scores were the highest at baseline and at endline, while F-ACT+ Minus 5 values overtook F-ACT values at endline. Although we had four variants of the F-ACT tool, we opted to use the F-ACT+ Minus 5 results for further data analysis because they are localized and therefore more representative of the local context (see detailed results for the other variations in the appendix of this paper).

Comparing the overall performance based on F-ACT+ Minus 5 for the ABCD and non-ABCD samples (Figure 3), it is apparent that the ABCD sample had considerably lower values at baseline, but

sampled from other Regreening 'intensification, sub-locations, while the Comparison households were sampled from Regreening 'scale-out' sub-locations. We hence expected prior exposure to Regreening to be twice as high among ABCD households.

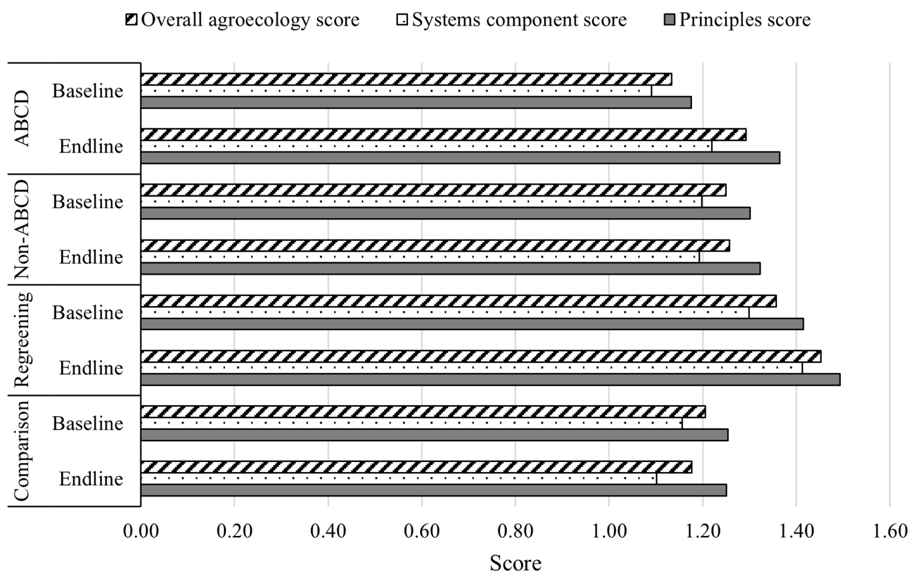

FIGURE 3
Summary performance of samples at baseline and endline based on F-ACT+ Minus 5. Source: Survey data (2023).

slightly higher values at endline. However, when looking at the non-ABCD sub-samples, namely the Regreening and the Comparison sub-samples, there is a strong difference at both baseline and endline, with Regreening continuing to progress further from previous considerably higher values, while Comparison values regressed slightly.

Considering the agroecology principles indicators scores using F-ACT+ Minus 5 (Table 9), the ABCD and non-ABCD samples followed similar overall trends. For both samples, the highest scores at baseline were for recycling (principle 1), input reduction (2), governance (12), (and input reduction, 2, for non-ABCD). At endline, the values for governance (12) and recycling (1) remained high, while social values and diets (9), as well as connectivity (11) improved considerably. However, there are clear differences between the samples. The ABCD sample showed improvements in 11 of the 13 principles, nine of which were significant, including six of the seven principles that fall under the operational principle of social equity, as well as input reduction (2), biodiversity (5), synergies (6), and economic diversification (7). The strongest improvement was observed in economic diversification (7), followed by social values and diets (9) and co-creation (8). A significant negative change was observed in input reduction (2). In the non-ABCD sample, improvements were recorded in only seven principles. Significant positive changes were observed in social values and diets (9) and connectivity (11), while significant negative trends were seen in recycling (1), input reduction (2), and fairness (10).

Looking at the scores for the agroecosystem component indicators using F-ACT+ Minus 5 (Table 9), the trends were similar in both samples as well. At baseline, the soil (1) system component was addressed most, followed by livestock (4), household (8), pest and disease (6), and community (10), while workers (9) and energy (7) were addressed least. At endline, soil (1), livestock (4), and household (8) continued to dominate, while there was considerable variance between the samples in other components. Again, baseline scores were higher for the non-ABCD sample than among the ABCD sample, except in the policy (12), value chain (11), and "other" (13) components. Looking at the difference in performance for the ABCD sample, there were significant positive changes in a nine of the 13 system components, including all three non-farm components (10–12) and the "other" (13) component, as well as significant negative trends in livestock (4) and workers (9). The strongest positive trends were in pest and disease (6), household (8), and value chain (11). In the non-ABCD sample, there were four significant positive changes in soil (1), pest and disease (6), policy (12), and value chain (11), while there were significant negative trends in four components, including livestock (4), trees (5), and workers (9).

3.3 Average treatment effect on the treated of the ABCD in Regreening project

Considering the treatment effect on the treated for the ABCD project using F-ACT+ Minus 5 (Table 10; details for the other tool variants are in Supplementary Table S4), the scores were significantly higher in the ABCD than in the non-ABCD sample for 10 of the 13 principles—that is all but animal health (4), social values (9) and connectivity (11). Comparing ABCD with the Regreening and Comparison samples, the difference between ABCD and Comparison was considerably greater than between ABCD and Regreening. Differences in ATT between ABCD and Regreening were more nuanced and significant in only six principles, namely input reduction (2), soil health (3), biodiversity (5), synergies (6) economic diversification (7), and co-creation of knowledge (8). At the same

TABLE 9 Comparison of performance between ABCD and non-ABCD based on change in principle and component scores between baseline and endline according to F-ACT+ Minus 5 tool.

Principle	ABCD				Non-ABCD			
	Baseline	Endline	Test of difference		Baseline	Endline	Test of difference	
			Difference	*t*-test			Difference	*t*-test
Recycling (1)	1.887	1.833	−0.054	−1.401	1.926	1.808	−0.118	−2.801***
Input reduction (2)	1.476	1.406	−0.070	−1.795*	1.649	1.374	−0.275	−7.331***
Soil health (3)	0.950	1.134	0.184	4.020***	1.058	1.120	0.062	1.184
Animal health (4)	1.186	1.192	0.006	0.105	1.252	1.274	0.022	0.376
Biodiversity (5)	1.016	1.148	0.132	3.343***	1.194	1.167	−0.027	−0.673
Synergies (6)	0.742	0.979	0.237	4.779***	0.972	0.953	−0.019	−0.348
Economic diversification (7)	0.793	1.215	0.422	11.448***	1.050	1.099	0.049	1.173
Co-creation of knowledge (8)	0.874	1.276	0.402	7.451***	1.057	1.054	−0.003	−0.048
Social values and diets (9)	1.314	1.606	0.292	7.674***	1.359	1.635	0.276	6.039***
Fairness (10)	1.181	1.418	0.237	3.807***	1.405	1.203	−0.202	−3.078***
Connectivity (11)	1.232	1.587	0.355	3.052***	1.217	1.682	0.465	3.816***
Land and natural resource governance (12)	1.423	1.655	0.232	3.535***	1.550	1.542	−0.008	−0.115
Participation (13)	1.216	1.301	0.085	1.442	1.233	1.280	0.047	0.760
Component								
Soil (1)	1.862	1.981	0.119	3.254***	1.903	1.985	0.082	1.859*
Water (2)	0.907	1.004	0.097	2.528**	1.034	1.031	−0.003	−0.074
Crops (3)	1.110	1.071	−0.039	−0.843	1.250	1.177	−0.073	−1.460
Livestock (4)	1.455	1.291	−0.164	−2.546**	1.576	1.242	−0.334	−5.696***
Trees and woody species (5)	1.092	1.124	0.032	0.722	1.291	1.138	−0.153	−2.852***
Pest and disease (6)	1.248	1.560	0.312	8.847***	1.380	1.464	0.084	2.631***
Energy (7)	0.423	0.645	0.222	4.145***	0.654	0.667	0.013	0.219
Household (8)	1.325	1.654	0.329	7.652***	1.504	1.473	−0.031	−0.766
Workers (9)	0.601	0.460	−0.141	−1.727*	0.890	0.509	−0.381	−4.007***
Community (10)	1.224	1.426	0.202	4.137***	1.319	1.321	0.002	0.033
Value chain (11)	1.011	1.346	0.335	6.313***	0.931	1.340	0.409	6.869***
Policy (12)	1.226	1.419	0.193	2.327**	1.186	1.463	0.277	2.967***
Other (13)	0.700	0.880	0.180	3.256***	0.663	0.706	0.043	0.649
N	248				228			

*, **, and *** denote statistical significance at the 10, 5, and 1% levels, respectively. Source: Survey data (2023).

time, the improvement in governance was significantly (10%) higher in the Regreening sample. All the significant differences between the ABCD and non-ABCD samples were also evident between the ABCD and Comparison samples, except for biodiversity (5), while the Comparison sample had a significantly (10%) higher improvement in connectivity (11).

TABLE 10 Comparison of estimates of the ATT on agroecology principles and system components from the DRDID estimator based on F-ACT+ Minus 5 tool variation.

Principle	ABCD vs. non-ABCD	ABCD vs. Comparison	ABCD vs. Regreening
	ATT (Std.Err.)	ATT (Std.Err.)	ATT (Std.Err.)
Recycling (1)	0.113* (0.059)	0.152** (0.060)	−0.052 (0.074)
Input reduction (2)	0.214*** (0.058)	0.188*** (0.058)	0.199* (0.104)
Soil health (3)	0.210** (0.082)	0.121 (0.081)	0.372*** (0.122)
Animal health (4)	0.055 (0.089)	−0.010 (0.091)	0.100 (0.148)
Biodiversity (5)	0.176*** (0.061)	0.108 (0.069)	0.250*** (0.079)
Synergies (6)	0.341*** (0.089)	0.247*** (0.078)	0.372** (0.159)
Economic diversification (7)	0.396*** (0.058)	0.393*** (0.059)	0.306*** (0.094)
Co-creation of knowledge (8)	0.375*** (0.076)	0.393*** (0.084)	0.366*** (0.137)
Social values and diets (9)	0.090 (0.067)	0.069 (0.074)	0.039 (0.103)
Fairness (10)	0.328*** (0.098)	0.351*** (0.116)	0.158 (0.156)
Connectivity (11)	−0.150 (0.183)	−0.367* (0.211)	−0.074 (0.343)
Land and natural resource governance (12)	0.270*** (0.097)	0.438*** (0.116)	−0.339* (0.172)
Participation (13)	0.174** (0.085)	0.257*** (0.089)	−0.164 (0.236)
Component			
Soil (1)	0.078 (0.054)	0.010 (0.063)	0.172* (0.099)
Water (2)	0.189*** (0.069)	0.097 (0.060)	0.279*** (0.086)
Crops (3)	0.074 (0.077)	0.037 (0.073)	0.060 (0.146)
Livestock (4)	0.203** (0.080)	0.336*** (0.090)	−0.126 (0.117)
Trees and woody species (5)	0.218*** (0.080)	0.186** (0.075)	0.146 (0.134)
Pest and disease (6)	0.247*** (0.054)	0.150*** (0.052)	0.339*** (0.077)
Energy (7)	0.173** (0.085)	0.127 (0.097)	0.332** (0.147)
Household (8)	0.370*** (0.057)	0.450*** (0.066)	0.128 (0.105)
Workers (9)	0.228 (0.143)	0.518*** (0.135)	−0.393 (0.331)
Community (10)	0.226*** (0.068)	0.352*** (0.075)	−0.035 (0.132)
Value chain (11)	−0.048 (0.100)	−0.226** (0.103)	0.090 (0.113)
Policy (12)	0.107 (0.137)	0.333** (0.153)	−0.758** (0.362)
Other (13)	0.199** (0.090)	0.281*** (0.099)	−0.150 (0.182)
N	476	409	315

*, **, and *** denote statistical significance at the 10, 5, and 1% levels, respectively. Values in parentheses are standard errors. Source: Survey data (2023).

Looking at the performance of the agroecosystem components (Table 10; and Supplementary Table S4), the ABCD sample had significantly higher improvements than the non-ABCD sample in eight of the 13 system components, including in water (2), livestock (4), trees (5), energy (7), pest and disease (6), household (8), community (10), as well as “other” (13).There was a much stronger difference between ABCD and Comparison than between ABCD and Regreening. Comparing ABCD and Regreening, the ATT was significantly stronger in the ABCD sample in soil (1), water (2), household (8), and pest and disease (6), while it was stronger in the Regreening sample in policy (12). Comparing ABCD and Comparison, the ABCD sample’s ATT was significantly higher in all but the soil (1), water (2), crops (3), energy (7), and value chain (11) components, and hence eight of the 13 system components. Interestingly, the Comparison sample’s ATT was significantly (5%) higher in the value chain component.

Applying the same estimation strategy to the summary principles, system components, and overall agroecology scores (Supplementary Table S5), the positive changes were significantly higher for the ABCD sample than for the non-ABCD sample (at the 1% level). The highly significant difference in the positive change for all three estimates between the ABCD and non-ABCD was also observed between ABCD and Comparison samples, but not as comprehensively between the ABCD and Regreening samples. Here, while the ATT was stronger for all three scores in the ABCD sample, it was only significant (at the 10% level) for the principles score in the F-ACT+ tool variant.

TABLE 11 Comparison of DRDID estimates of the ATT for the eight ABCD and six core F-ACT criteria.

Criteria	System component	Agroecological principle	Subsample comparison		
			ABCD vs. non-ABCD	ABCD vs. Comparison	ABCD vs, Regreening
			ATT (Std.Err.)	ATT (Std.Err.)	ATT (Std.Err.)
ABCD "plus" criteria	Value chains	Co-creation (8): Access and sharing of market prices	0.184 (0.122)	0.294** (0.137)	0.005 (0.141)
		Social values & diets (9): Care for benefit of local buyers	0.360*** (0.114)	0.464*** (0.122)	−0.006 (0.152)
		Fairness (10): Fair access to markets	0.388*** (0.147)	0.359** (0.165)	0.418 (0.256)
		Participation (13): Producer group participation	−0.080 (0.116)	−0.105 (0.120)	−0.031 (0.206)
	Household	Social values & diets (9): Self-efficacy	0.009 (0.078)	0.054 (0.092)	−0.139 (0.095)
		Participation (13): Group saving and loaning	−0.025 (0.118)	0.020 (0.129)	−0.271* (0.144)
	Community	Social values & diets (9): Community respect and action	0.545*** (0.140)	0.628*** (0.151)	0.389 (0.258)
		Participation (13): Strategic collaboration	0.334*** (0.127)	0.644*** (0.128)	−0.536*** (0.203)
Core F-ACT criteria	Value chains	Economic diversification (7): Sufficient and diverse farm income	1.168*** (0.109)	1.352*** (0.120)	0.906*** (0.139)
		Co-creation (8): Farm records	0.813*** (0.111)	0.912*** (0.130)	0.633*** (0.179)
		Fairness (10): Equal decision-making men and women	0.149 (0.131)	0.338** (0.148)	−0.290 (0.196)
	Community	Economic diversification (7): Farmer group for joint sales membership	0.296*** (0.074)	0.348*** (0.083)	0.155 (0.160)
		Co-creation (8): Co-creation platform participation	0.118 (0.122)	0.230* (0.138)	0.064 (0.198)
		Participation (13): Collective farming or landscape management action	0.429*** (0.148)	0.747*** (0.163)	−0.147 (0.310)
N			476	409	315

*, **, and *** denote statistical significance at the 10, 5, and 1% levels, respectively. Values in parentheses are standard errors. Source: Survey data (2023).

Isolating the eight ABCD-focused "plus" criteria, as well as the six individual F-ACT criteria for which we predicted particularly strong effects (Table 11), the ATT is highly significantly stronger in the ABCD sample than in the non-ABCD sample for eight of the 14 criteria. These include care for local customers, fair access to markets, community respect and action, and strategic collaboration, as well as sufficient and diverse farm income, keeping of farm records, farmer group membership, and collective farming or landscape management action. Again, the difference between the ABCD and Comparison samples is more pronounced, with a significant positive ATT in 11 of the 14 criteria. In addition to the eight mentioned, the positive trend in access to and sharing of market prices, equal decision-making, and participation in co-creation platforms was also significantly higher in the ABCD sample. The effect is much more nuanced with the Regreening sample performing significantly better in two ABCD criteria (group saving and loaning; strategic collaboration), and the ABCD sample in two highlighted regular F-ACT criteria (sufficient and diverse farm income, farm record keeping).

Finally, the DRDID estimates of the performance of the different group types between the ABCD and the non-ABCD samples showed clear differences (Figure 4; more details in Supplementary Table S6), with groups falling under Type 1 performing slightly better than Type 3, and both outperforming groups of Type 2 and 4 by far. While the differences between Type 1 and 3 and between Type 2 and 4 were not significant, the differences between the former two and the latter two were significant at the 10% level.

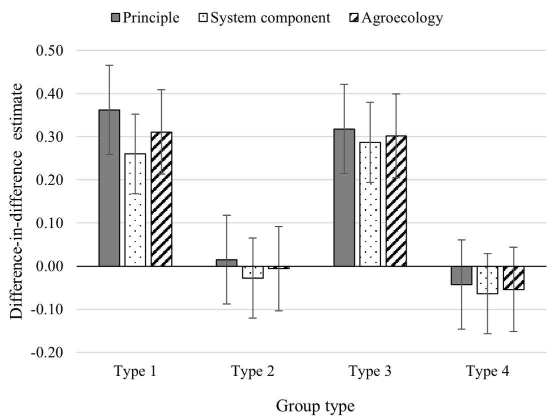

FIGURE 4
Difference-in-differences estimates in overall agroecological integration, system components, and agroecology scores by group type in the ABCD vs. non-ABCD samples using F-ACT+ Minus 5. Source: Survey data (2023).

4 Discussion

4.1 Key results confirm ABCD sample's accelerated agroecological integration

The results presented manifest accelerated agroecological integration among the ABCD participants. First, as expected, the ABCD sample improved significantly in nine of the 13 principles, including all principles nested under the social equity operational principle, as well as economic diversification (7), alongside biodiversity (5), synergies (6). The strongest improvements were observed in economic diversification (7), social values and diets (9) and co-creation (8), while the expected improvement in participation (13) was not as significant as expected, and a significant negative trend was observed in input reduction (2). Regarding the changes observed in the different system components, the expected positive effects were confirmed in value chain (11), household (8), and community (10), alongside highly significant changes in soil (1), water (2), pest and disease (6), policy (12), and "other" (13). At the same time, significant negative effects were observed for livestock (4) and workers (9). Of the nine significant positive trends, the strongest were in pest and disease (6), household (8), and value chain (11). These results were largely confirmed in the ATT analysis using the DRDID method, which directly compared the performance of the ABCD sample with that of the non-ABCD respondents. The ATT was significantly higher in the ABCD sample for 10 of the 13 principles, and in eight of the 13 system components. However, several principles that initially showed the greatest improvements did not have significant ATT scores, including in social values and diets (9) and connectivity (11). At the same time, they showed significantly higher improvements in recycling (1), input reduction (2), and participation (13) that were not reflected in the initial *t*-tests. Notable differences from the initial tests in the system components were significant positive ATT values in livestock (4) and biodiversity (5), while ATT values in soil (1), value chain (11), policy (12) were not significant. Looking specifically at the ABCD "plus" criteria, as well as the six highlighted individual "core" F-ACT criteria, the positive trends in the ABCD sample were significantly higher than among the non-ABCD sample in eight of the 14 specific criteria. Again, the difference with the Comparison sample was substantial, and significant in 11 criteria, while the difference with the Regreening sample was much more nuanced.

Consistent with our overall predictions, the improvements observed in the ABCD sample were generally significantly higher than those observed in the non-ABCD sample. Furthermore, there was a clear difference in performance between the ABCD sample and the Regreening sample, and an even clearer difference with the Comparison sample. This confirms our main hypothesis, although the significance varies depending on the group pairing. Looking more specifically at the performance of the different ABCD groups more specifically, as expected, the ABCD group types 1 and 3, characterized by high assets/ high agency, and by low assets/high agency, respectively, performed statistically significantly better than types 2 and 4. This is in line with the core argument made in Fuchs et al. (2021b) that a purposive participant selection process, which *ex ante* screens the suitability of for potential participants with regard to the specific project content in order to "establish a mutual match," can help" to eliminate procedural inefficiencies and considerably improve development effectiveness, efficiency, and sustainability.

4.2 How asset-based and agency-centered approaches and tools scale sustainable practice

While the detailed results of the contribution analysis are reported in Fuchs et al. (2024), two dominant underlying mechanisms that supported Regreening outcomes in our contexts can be highlighted. First, in line with the conceptual congruence between ABCD and agroecology, and the applicability of the agroecology framing for the promoted "Regreening practices," ABCD *intrinsically* supports agroecology through its focus on resource appreciation and peoples' self-mobilization to use their existing resources efficiently and sustainably. As discussed above, one of the key differences between ABCD and other approaches is that ABCD explicitly invites people to think about their own individual and collective contribution by starting with what they already have in terms of human, social, natural, economic, and other capital. On the other hand, while many other approaches engage people in conversations, visioning, and decision-making, they often do so without centering them and what *they* can do to make a positive contribution to their lives and landscapes. The second mechanism concerned ABCD project participants who, through the social asset assessment, gained a better understanding the identities, interests and preferences (IIP) of associations and institutions that are active in their community. This helped empowered and interested community members to seek targeted support from and strategic collaboration with existing external actors and their projects based on an alignment of their interests with IIPs of the respective external actors—in this case Regreening Africa. Similarly, the ABCD participants gained a better understanding of the IIP of other community members through the human asset assessment. This contributed to Regreening Africa lead-farmers being recognized and approached by other community members for exchange and learning opportunities. In turn, this community-driven demand helped Regreening Africa and its local lead-farmers to be more effective, efficient, and sustainable in their

Regreening capacity building, as this interaction was driven by the demand of empowered community members who differentiated between those change pathways that they could drive by themselves, and those that were pursued through targeted collaboration and external support.

Comparing the performance of the ABCD sample with that of the Regreening sample, the positive effect remained significant but nuanced. There are several possible explanations. One general observation relates to the fact that the Regreening sample started from a much higher level than the ABCD sample, whose baseline scores were even considerably lower than the ones of the Comparison sample. At the same time, although we adapted our sampling framework to Regreening's, which was designed to ensure a similar level of prior engagement with Regreening Africa among the ABCD and Regreening samples, the actual percentage was much higher among the Regreening sample. In addition, the non-ABCD sample held and operated significantly bigger land sizes, and the percentage of Type 4 groups (which we projected would do least well) was significantly lower among the non-ABCD sample, while the percentage of Type 3 groups (which we projected would do the best) was considerably, although not significantly, higher.

Furthermore, while not expected to be a significant *intrinsic* effect of ABCD, it is possible that the positive outcomes in soil, water, and pest and disease (management) were related to the fact that our team provided technical training in response to a demand for on-farm agroecological practices that focused specifically on these three areas. While the data used in this study did not provide insight into this matter, additional data collected and reported in Fuchs et al. (2024) allow for a case to be made that ABCD is an excellent approach to co-learning in the broader context of context-specific technical knowledge dissemination and co-creation. As introduced, we typically use ABCD to define responsive action plans. While the research design in the "ABCD in Regreening" project did not allow for much responsive action, this result allows a case to be made for its value as a synergistic approach to projects that aim to promote specific land-based practices, such as Regreening Africa, which has the potential to accelerate and deepen their impact and reach.

ABCD's clear positive contribution to principles that fall under the social equity operational principles and off-farm system components can be invoked in response to critiques that argue that by focusing and building on existing assets and strengths, community-driven development allegedly fails to challenge the political, economic, and social context and thus perpetuates rather than challenges existing structures and injustices (Brooks and Kendall, 2013; Ennis and West, 2013; Friedli, 2013; McConnell, 2021). Our findings contribute to others that show that ABCD allows for addressing situations in which the "strengths and assets of people in communities have been undervalued, weakening the potential for citizens to engage as active partners in social change" (Peters et al., 2021, p. 14). Instead, ABCD "combines different forms of active citizenship where people bring about change at their own pace, on their own terms. Structural change may not be the starting point, but the collective agency built through identifying and mobilizing local assets (…)" (*ibid.*, p. 15) is an important ingredient for self-actualization and collective mobilization that enables communities to advocate for social change. While power imbalances between external actors and project participants, as well as among community members themselves, can, of course, not be avoided or solved by asset-based and agency-focused engagement approaches, ABCD is an approach that supports transformation through intrinsic bottom-up empowerment, and provides guidelines for purposive, reflexive, and methodical engagement methods and modalities that (e.g., Fuchs et al., 2021b).

The study found significant positive changes in the level of agroecological integration among the ABCD sample, and significantly higher improvements than among the non-ABCD sample. This makes it possible to argue for the overall intrinsic positive effect of ABCD, and its promise as a synergistic approach to support projects aiming at sustainable behavior change at the individual and collective levels. Adopting an ABCD approach allows an external actor to play a facilitating and supportive role, from which communities can seek targeted support. Providing external support in a *responsive* rather than prescriptive manner allows communities' control and dignity to be maintained and respected, thus avoiding top-down dissemination approaches. It also allows external actors to understand which entry points and framings to use in their work. This makes it more likely that communities implement and adopt knowledge that is co-created with external actors through community-demand-driven co-learning processes. Ultimately, it allows external actors and their local partners to work together in those areas and domains where there is a "mutual match," and where they are most likely to benefit from each other, rather than imposing from the outside a singular development model designed by a particular external partner that is likely to oversimplify the complexity of local realities and therefore risks being rejected outright. It also helps external actors identify and engage with community members who are interested in what they are proposing. This helps to build sustainable relationships based on mutual recognition and dignity, which helps to manage mutual expectations. The proposed process aligns with the core hypothesis that many facets of development, such as adaptation, adoption, livelihood diversification etc., happen only when they are driven by empowered and enabled individuals and communities themselves, and that their sustainability may be compromised if fostered and facilitated through top-down processes (Fuchs et al., 2021b).

4.3 Usefulness of the F-ACT+ tool for assessing engagement in sustainable land management practices

Considering the usefulness of the F-ACT+ tool in the context of evaluating the contribution of the "ABCD in Regreening" project to strengthening the results of Regreening Africa, several observations can be made. First, the structured and methodical process to first of first defining what matters, then measuring what matters, and generating data on what matters, ine line with the proceeding proposed in (Lamanna et al., 2024), was very useful and confirms the suitability of the F-ACT+ tool. The tool proposes a systemic approach to evaluation that embraces complexity and includes many of "social" outcomes emphasized by ABCD. It also embeds the assessment part in other activities including visioning and action planning for sustainable development at the household level—much like ABCD itself as well. In general, the tool itself is easy to use, the questions are usually clear, and the response options are mostly well structured in 4-point response formats that allow for the levelling of answers. The data representation options are interesting, and the overall embedding of the quantitative assessment part in a contextualization, an inspiration, and a planning part demonstrates the tool's appropriateness for a research-in-development setting.

However, we found several weaknesses in the original F-ACT tool. In general, answer options for some criteria are not equidistant (i.e., the difference between answer options 3 and 4 is often greater than between 1 and 2, or between 2 and 3), and answer options across criteria sometimes appear unbalanced (i.e., an answer option that is associated with the numerical number 1 in one question would receive a 3 in a similar question). The spacing of response options sometimes reveals a potential underlying conceptual bias: some response options appear to be biased toward diversification, with the highest scores given for the greatest diversity of practices, tree species, crop species etc., without explicit consideration of their contextual suitability. While general diversification is certainly an underlying agroecological principle, the diversification imperative implicit in the tool sometimes seems to contradict the options by context paradigm (Coe et al., 2014). In addition, as discussed in the context of the "Minus 5" variations of the tool, some questions and response options seem Eurocentric and not adapted and relevant to the Kenyan context. Because the tool is designed as a questionnaire that can be used to collect primary data from households at the farm level, it is suitable for monitoring change over time, and can therefore be used for baseline, midline and endline data collection. However, because of its broader objectives, it is however not as extractive as other monitoring and evaluation approaches. Yet, the tool also includes several indicators that are rather unlikely to change over short periods of time, which may require adaptation if the tool is to be used to monitor changes over time rather than for point-in-time insights. Furthermore, despite the inclusion of off-farm system components (albeit few compared to on-farm components) and at least six principles directly related to social characteristics that support social equity, explicit questions to assess the social-cultural and socio-economic dynamics that contribute to deepening the level of agroecological integration remain rather few. While our team's efforts to supplement the tool have helped to address this imbalance, the official version of the tool could benefit from further related adaptations.

4.4 Sustainable scaling requires tools and processes that foster *responsive* external support for community empowerment, agency, and action

The Regreening Africa project team sought support from the ABCD team with an explicit interest in identifying sustainable scaling mechanisms that would help them achieve their "ambitious" land restoration targets, and reach more people more quickly and more sustainably. We developed a methodical and stepwise conceptual and analytical framework to demonstrate in detail that the adoption of an asset-based and agency focused engagement approach made an intrinsic positive contribution through community-driven scaling of Regreening practices. The Regreening team also introduced several other knowledge dissemination and scaling practices in Kenya, including media engagement in radio and television, road shows, soccer tournaments, farmer field days, and participatory videography (Regreening Africa, 2020). In addition, the ABCD team also collaborated with Regreening Africa to develop a Sustainability Planning approach that combines previous ABCD and SHARED work (Fuchs et al., 2021a), which was rolled out in all eight project countries. Regreening Africa celebrated ABCD as one of its "success stories" in light of the positive evaluation by implementing staff and project participants (Regreening Africa, 2022a, 2022b).

ABCD is being used by communities around the world to self-organize. In contexts such as the "ABCD in Regreening" project, external actors use ABCD as an intentional co-design approach that allows them to "bridge the divide in community development… [and link] community demands and responsive external support" (Fuchs, 2018, title) to promote sustainable behavioral change in a research-in-development context. While there are many interesting participatory engagement approaches being used in similar contexts, ABCD's approach and practice differ from others in that it proposes a combination of a particular set of framings, methods and mechanisms, and processes. ABCD's framing includes an inclusive and comprehensive focus on existing assets (what *you* already *have*) and agency (what *you* can *do* with it). The ABCD methods and mechanisms emphasize self-assessment, self-realization, self-actualization, and self-evaluation. Finally, the ABCD processes focus on attitudes about assets and agency before addressing behaviors.

Agroecology is fundamentally focused on the co-creation and co-design of knowledge and contextualized solutions. It is committed to transdisciplinary approaches that are problem-focused, solution-oriented, inclusive, and reflexive (HLPE, 2019; Sinclair, 2021). Our study affirms the importance of engagement processes that, first, promote self-reflection, self-belief, and self-mobilization among communities to sustainably mobilize their assets for individual and collective action, and, second, promote critical self-reflection among implementing external actors to ensure that they focus on sustainable relationship building and responsive action that aligns with their IIP while being scientifically sound. Due to its outcome focus, our study provided limited insights into these and other specific mechanisms and what, if any, specific contribution claims could be verified. Our separate work on theory-based contribution analysis (Fuchs et al., 2024) meaningfully enriches this study. The land restoration agenda must be driven by local communities to build climate-resilient livelihoods and landscapes, the sustainability of which depends on communities around the world individually and collectively defining, co-creating, and implementing context-specific land restoration options. By adopting an asset-based and agency-focused approach to engagement, external actors can accompany community-driven change and support broad agroecological transitions. Further research on the impact of specific co-design tools and methods, as well as on the processes and behaviors of external actors, will allow to strengthen their capacity to develop and implement sustainability-promoting approaches that help to address the pressing crises of our time in a transdisciplinary manner.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/TQJ2PJ.

Ethics statement

Ethical approval was obtained in accordance with the legal legislation and institutional requirements. The participants provided their informed consent as part of the surveys.

Author contributions

LF: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Visualization, Writing – original draft, Writing – review & editing. LO: Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. LK: Investigation, Writing – original draft, Writing – review & editing, Conceptualization. VA: Conceptualization, Investigation, Writing – original draft, Writing – review & editing. SO: Data curation, Formal analysis, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. The work was funded by Biovision Foundation for Ecological Development under the grant number BV DPE_010/2021-2023.

Acknowledgments

We acknowledge the support, interest, and hands-on involvement of Biovision Foundation, especially project officers Fabian Kohler and Adrian Bolliger. We also thank the CIFOR-ICRAF Systems'/Agroecology team lead Fergus Sinclair for his support in linking us to the Regreening Africa project, which proved to be an ideal context in which to conduct this research. We are greatly indebted to Susan Chomba and Mieke Bourne, the successive Regreening leads at CIFOR-ICRAF, for their interest, enthusiastic support, and dedication. We also thank the broader Regreening Africa team at CIFOR-ICRAF and World Vision Kenya, including Constance Neely, Winnie Achieng', Karl Hughes, Hilda Kegode, Tesfaye Woldeyohanes, Charles Odhiambo and others. We are grateful for the critical reflections and support from other CIFOR-ICRAF scientists, including Richard Coe and Christine Lamanna. Beyond that, we acknowledge the unwavering support and interest of our legacy donor, the Comart Foundation, which provided seed funding for this project. Their revolving trust fund set up to support our team's participation in courses offered by our long-term action research partner, the Coady Institute, which has greatly facilitated the ABCD team's and others' access to sustainable engagement and co-design theories, methods, and practices. We also thank the global ABCD community of practice for the continuous exchange, encouragement, and energy.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2024.1449615/full#supplementary-material

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TYPE Original Research
PUBLISHED 27 November 2024
DOI 10.3389/fsufs.2024.1455581

OPEN ACCESS

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RECEIVED 27 June 2024
ACCEPTED 11 November 2024
PUBLISHED 27 November 2024

CITATION
Jakku E, Fleming A, Fielke S, Snow S, Malakar Y, Cornish G, Hay R and Williams L (2024) Advisors as key partners for achieving adoption at scale: embedding "My Climate View" into agricultural advisory networks.
Front. Sustain. Food Syst. 8:1455581.
doi: 10.3389/fsufs.2024.1455581

Advisors as key partners for achieving adoption at scale: embedding "My Climate View" into agricultural advisory networks

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Introduction: This paper examines the role of agricultural advisors as key partners for scaling adoption of long-term climate information. Agri-food sectors across the world face significant challenges in responding to climate change, which intersect with broader pressures driving transitions to more climate resilient and sustainable agri-food systems. Making better climate information available to farmers is a key part of responding to these challenges, since relevant and usable climate information can help farmers to adapt to future climate conditions. The development of climate services, which seek to provide climate information to assist with decision making, has therefore increased significantly over the last decade. The Climate Services for Agriculture (CSA) program provides long-term climate projections to help the Australian agriculture sector prepare for and adapt to future climate conditions. 'My Climate View' is an online tool produced by CSA, which provides localised and contextualised, commodity-specific climate information, through historic weather data and multi-decadal projections of future climate, aimed at Australian famers and farm advisors. Agricultural advisors have a critical yet often underutilised role as climate information intermediaries, through assisting farmers translate climate information into action.

Methods: This paper uses CSA as a case study to examine farmer-advisor interactions as a key adoption pathway for My Climate View. We interviewed 52 farmers and 24 advisors across Australia to examine the role of advisors as key partners in helping farmers to understand climate information and explore on-farm climate adaptation options.

Results and discussion: Interactions between farmers and their trusted advisors are an essential part of the enabling environment required to ensure that this long-term climate information can be used at the farm scale to inform longer-term decisions about climate adaptation. We use the concept of an interaction space to investigate farmer-advisor interactions in the adoption and sustained use of My Climate View. We find that although My Climate View is not a transformational technology on its own, its ability to enable farmers and advisors to explore and discuss future climate conditions and consider climate adaptation options has the potential to support transformational changes on-farm that are needed to meet the sustainability transition pressures that climate change presents.

KEYWORDS

climate services, climate projections, climate adaptation, Australian agriculture, agricultural innovation, behaviour change

1 Introduction

The global agri-food sector faces well-documented challenges in responding to climate change, which intersect with broader pressures, driving transitions to more climate resilient and sustainable agri-food systems (Howden et al., 2007; Zuccaro et al., 2020). Providing farmers with better climate information is a key component of responding to these challenges, where relevant and usable climate information can help support farmers to understand and respond to future climate conditions (Stone and Meinke, 2006). As a result, the development of climate services, which seek to provide climate information to assist with decision making, has increased significantly over the last decade (Jacobs and Street, 2020; Webber, 2019). In Australia, the Climate Services for Agriculture (CSA) program aims to provide multi-decadal climate projections (out to 2080s) to help the Australian agriculture sector prepare for and adapt to future climate conditions, funded by the Department of Agriculture, Fisheries and Forestry (DAFF) as part of the Future Drought Fund (FDF). CSA is a research and development program, involving scientific research, engagement, software development, product strategy and many other aspects of science and technology delivery, through collaboration between Australia's national science agency the Commonwealth Scientific and Industrial Research Organisation (CSIRO), and the Australian Bureau of Meteorology. "My Climate View"[1] is an online tool produced by CSA, which provides localized and contextualized, commodity-specific climate information, through historic weather data and multi-decadal projections of future climate, aimed at Australian famers and farm advisors (Webb et al., 2023). My Climate View has a potentially valuable role to play in helping farmers explore long-term climate projections for their specific context and consider ways they could apply that information in their on-farm planning (Malakar et al., 2024a,b; Snow et al., 2024b). Interactions between farmers and their trusted advisors are an essential part of the enabling environment required to ensure that this long-term climate information can be used at the farm scale to inform longer-term decisions about climate adaptation (George et al., 2018).

This paper uses CSA as a case study to examine farmer-advisor interactions as a key adoption pathway for My Climate View. We draw on the concept of an interaction space (Hermans et al., 2023) to investigate farmer-advisor interactions in the adoption and sustained use of My Climate View. We examine the role of advisors as key partners in helping farmers to understand complex climate information and consider strategies for on-farm adaptations to future climate conditions, including the potential for advisors to act as climate intermediaries. In so doing, we explore how CSA is working in partnership with local advisory networks to ensure that My Climate View is accessible and useful for supporting climate adaptation decisions. We find that although My Climate View in and of itself is not a transformational technology, its ability to enable farmers and advisors to explore and discuss future climate conditions and consider implementing climate change adaptation actions has the potential to support transformational changes on-farm that are needed to respond to the transition pressures brought about by climate change. In the next section, we provide an overview of the theoretical background to our research, focusing on the literature on agricultural innovation systems and introducing the conceptual framework of an agricultural innovation interaction space. We then provide details on our materials and methods before presenting key themes from our research results, and then discuss the implications of our findings.

1 https://myclimateview.com.au/

2 Theoretical background: agricultural innovation systems and advisors as climate intermediaries

Our focus on the role of advisors as key innovation partners for scaling adoption is theoretically informed by the literature on Agricultural Innovation Systems (AIS) and Agricultural Knowledge and Innovation Systems (AKIS), a branch of innovation studies that provides a foundation for understanding the complex social processes and multiple networks that shape innovations in agriculture (Hall et al., 2003; Kernecker et al., 2021; Klerkx and Leeuwis, 2009a; Morriss et al., 2006; Turner et al., 2016). An underpinning feature of the AIS perspective is a recognition of the limitations of linear, transfer of technology approaches, which assume that knowledge about an innovation is transferred from "experts" (e.g., researchers) to intermediaries (e.g., advisors), and then on to farmers for "adoption" (Klerkx et al., 2012; Kuehne et al., 2017; Vanclay and Lawrence, 1994). However, this simplistic technology transfer and adoption approach fails to account for the complex interactions between networks of people, organizations and contextual factors, all of which are an integral part of the dynamic process of agricultural innovation (Hermans et al., 2023; Klerkx et al., 2012; Montes de Oca Munguia et al., 2021). The related concept of scaling, which refers to the increased use of innovations beyond those involved in the initial design and testing, is also subject to similar critiques regarding simplistic, linear models of technology adoption (Hermans et al., 2021; Sartas et al., 2020; Woltering et al., 2019). The social context of technology development and use is critical to adoption in agriculture (Glover et al., 2019; Hermans et al., 2023; Montes de Oca Munguia et al., 2021), as is the case in technology adoption more generally (Talukder and Quazi, 2011). An AIS or AKIS approach recognizes that technologies are shaped by dynamic processes across time and space, in response to local contexts and through ongoing social learning and development, and the process of scaling innovations is complex and dynamic (Glover et al., 2019; Hermans et al., 2023; Sartas et al., 2020; Wigboldus et al., 2016).

The AIS approach focuses on the range of actors and coordinated interactions involved in research, development, support and implementation of technological innovations in agriculture (Klerkx et al., 2012). This shift away from linear transfer of technology approaches includes an emphasis on participatory and collaborative approaches to innovation, which highlights the value of co-creating research questions and collaboratively conducting research and technology development (Lee et al., 2012; Srinivasan et al., 2019). This also involves coordinating social, economic, and regulatory systems to provide an enabling environment that results in innovations that are better suited to their context of use, enhancing their uptake and impact (Fielke and Srinivasan, 2018; Klerkx and Nettle, 2013; Klerkx et al., 2017b). Processes of participatory design and collaboration are identified as important factors for the successful implementation of agricultural innovations (Ayre et al., 2019; Fielke et al., 2017; Rijswijk et al., 2019; Stitzlein et al., 2020). As a result, there has been a rise in projects focusing on co-design, co-development and other forms of collaboration in climate and agricultural services, collectively referred to as "co-production" (Dolinska et al., 2023; Fleming et al., 2023; Lu et al., 2022).

Agricultural advisory services are an important part of the agricultural innovation system (Klerkx et al., 2017a). Within AIS scholarship, agricultural advisory services are defined in a very broad sense, to include "the entire set of organizations that support and facilitate people engaged in agricultural production to solve problems and to obtain information, skills, and technologies to improve their livelihoods and wellbeing" (Birner et al., 2009, p. 342). Therefore, we use the term advisors to encompass the wide range of professions in public, private and civil sector organizations with a role in sharing information and advice to support farmers and enhance their skills (Klerkx and Proctor, 2013; Knierim et al., 2017; Sutherland and Labarthe, 2022). Advisors can assist farmers with operational decisions (such as technical advice on crop selection, fertilizer inputs, or soil management), or strategic decisions (such as farm business planning or land management decisions), as well as providing support to meet regulatory requirements (Klerkx and Proctor, 2013; Nettle et al., 2018). Depending on geographical and commodity contexts, these advisors play different roles and may describe themselves as agronomists, extension officers, knowledge brokers, trainers, or consultants (Fielke et al., 2020; Sutherland and Labarthe, 2022). Advisors can also be part of more informal networks, such as industry representatives, committees, community leaders, mentors, social connections, friends and family, with roles such as network building and social support (Bechtet, 2023; Fielke et al., 2020). Furthermore, trends such as privatization, pluralism and digitalization are shaping agricultural advisory services, leading to institutional changes and an increasingly complex and dynamic context for advisors (Fielke et al., 2020; Knierim et al., 2017; Nettle et al., 2018; Rijswijk et al., 2019).

Advisors are key intermediaries within the AIS, due to their role in connecting multiple other actors (Kivimaa et al., 2019). Advisors can intermediate in different ways, including network-building and brokering for knowledge exchange (Bäumle et al., 2023; Hernberg and Hyysalo, 2024; Moss, 2009), as well as configuring knowledge to make it locally relevant (Duncan et al., 2020; Hakkarainen and Hyysalo, 2016; Hernberg and Hyysalo, 2024). Agricultural advisors are therefore excellently positioned "to act as climate information intermediaries and influence the use of climate science" because they already assist farmers to identify opportunities and support farmers with day-to-day decisions and future challenges (Haigh et al., 2015, p. 84). Prokopy et al. (2013) identify how advisors incorporate weather and climate information in their advice to farmers. Decisions are grouped into three temporal categories of: operational (lead time of days to weeks- e.g., when to spray); tactical (lead time of months- e.g., choice of varieties for next season); and strategic (lead time of a year or more- e.g., investment in irrigation, drainage or adoption of conservation practices). However, similar to farmers, advisors' use of climate information is often still predominantly concentrated around operational and tactical decisions, and long-term climate information is used less in advisors' day-to-day work than weather or seasonal climate information (Prokopy et al., 2013).

Nevertheless, given their important role as climate information intermediaries, advisors are key partners in co-production efforts along with farmers because advisors are often a key end-user of climate services. Co-production demonstrably increases user "fit" and improves relevance, usability and inclusivity (Fleming et al., 2023; Lu et al., 2022). Efforts to co-produce climate services with advisors include: MED-GOLD (Europe) (Dainelli et al., 2022), Climate Services for Agriculture (Australia) (Snow et al., 2024a), and Useful to Usable (USA) (Prokopy et al., 2017). However, "co-production alone does not guarantee dissemination" (Lu et al., 2022, p. 254). "Scaling" climate services additionally involves substantial effort into engagement and marketing of tools to build awareness and skills for use (Lu et al., 2022). Therefore, in addition to their role in co-production, advisors can play a central role in scaling climate services and supporting adaptive decisions. Compared with farmers, agricultural advisors were found more likely to be aware of available climate-decision-support tools, and more willing to use and recommend the tools to others (Lu et al., 2022). The centrality of advisors' role here is underscored by findings that 10% of farmers who identified they would not use the decision support tools, cited that they relied on advisors for those decisions (Lu et al., 2022). Therefore, advisors can assist with scaling in different ways. For instance, advisors often have large networks so they can scale climate services through personal recommendations. Moreover, advisors can disseminate information from climate services by incorporating it into their advice to farmers, even if they do not use or mention the climate service directly to the farmer.

2.1 Conceptual framework: agricultural innovation interaction space

Drawing on the AIS approach, Hermans et al. (2023) developed the concept of an interaction space, which they define as "a specific grounded space in such [AIS] systems, where social interactions and exchanges of information between different actors and institutions play out in practice" (Hermans et al., 2023, p. 2). As Figure 1 illustrates, this interaction space occurs at the interface between the research and development networks and farm system networks and features co-production and knowledge intermediation activities.

In this framework on agricultural innovation interaction space, the research and development networks (R&D) are driven by public and private sector agricultural research and development programs and projects and associated extension activities focused on developing and scaling innovations, while the farm system networks are the formal and informal networks of farmers and farmer groups where knowledge and information about innovations is shared, experimented with and shaped by the specific social, cultural and environmental contexts of local areas (Hermans et al., 2023). In the context of agricultural innovations, these interaction spaces therefore provide opportunities for researchers, funders, advisors and farmers involved in agricultural projects to exchange and construct socio-political and technical knowledge in a way that shapes the innovation process and outcomes. Trust is an important feature of innovation interaction spaces, with relational ties built on trust being central to innovation, knowledge sharing, and farmer and advisor relationships (Carolan, 2006; Eastwood et al., 2022; Hermans et al., 2023; Sligo and Massey, 2007). While there are multiple definitions and dimensions of trust (Blomqvist, 1997), personal or relational trust (Curry, 2010; Giddens, 1990) and institutional trust (Giddens, 1990; Putnam et al., 1993) are particularly important within agricultural innovation interaction spaces (Sutherland et al., 2013). Furthermore, trust in technology is

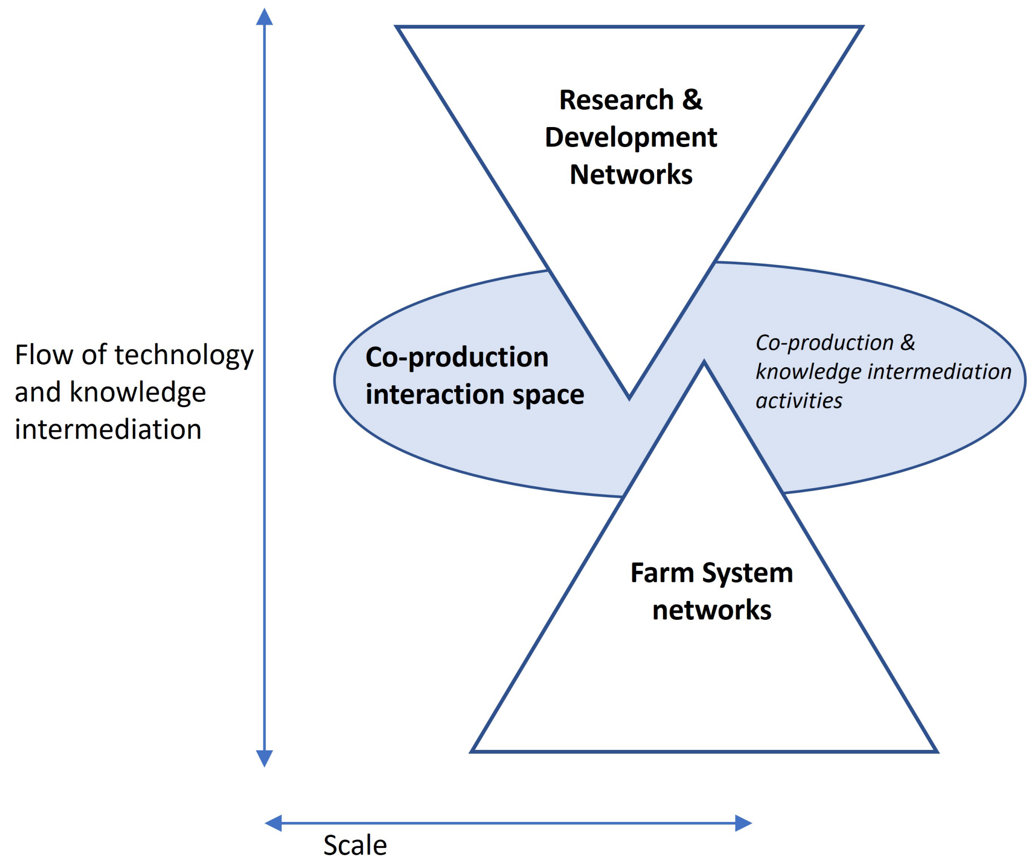

FIGURE 1
Agricultural innovation interaction space, adapted from Hermans et al. (2023, p. 3).

another important factor within the interaction space, which includes expectations about the relevance or usefulness of particular technologies featured within the interaction space (McKnight et al., 2011; Yeo and Keske, 2024). This is likely to be particularly relevant where there are multiple, sometimes conflicting, technological innovations within an interaction space, as can be the case with climate services.

Farmer engagement in the interaction space is vital, but so is the role of advisors as knowledge brokers and intermediaries in the social and technical innovation dynamics that shape the interaction space (Hermans et al., 2023). Using the conceptual lens of an interaction space to explore these innovation dynamics in our CSA case study allows us to examine "where and how socio-technical change is shaped by the relationships between agricultural development interventions, actors, local knowledge exchange and (social) learning processes" (Hermans et al., 2023, p. 2). The pivotal role of advisors in brokering knowledge between groups and catalyzing innovation is already well established, and the focus of a substantial body of literature (Caloffi et al., 2023; Feser, 2023; Howells, 2006; Klerkx et al., 2012). Knowledge brokers are a specific form of intermediaries, defined as individuals or organizations that mediate the flow of knowledge and information between a pair of unconnected actors (Boari and Riboldazzi, 2014; Burt, 2007). Their role can facilitate the introduction, understanding and adoption of digital technologies. Knowledge brokers are known and trusted "knowledge sources that support the exchange and integration of knowledge" (Crupi et al., 2020, p. 1264). The literature on knowledge brokers and intermediaries emphasizes the dynamic nature of intermediation (Kivimaa et al., 2019), the need to embed knowledge brokers in different levels of innovation structures (Kanda et al., 2019; Klerkx and Leeuwis, 2009b) and how relationships between advisors and farmers often extend well beyond the provision of technical advice (Cook et al., 2021). Much less explored, however, is the role of advisors as climate information intermediaries with respect to future climate information (Haigh et al., 2015).

We use the conceptual lens of an interaction space to explore the innovation dynamics in our CSA case study, to examine the role of agricultural advisors as key partners for scaling climate information. Our research objective is to understand how advisors can be important partners throughout the development of climate services and the dissemination of climate information at scale. Therefore, understanding how advisors perceive and use multi-decadal climate services helps us identify how agricultural advisors can help to scale adoption of this information.

3 Materials and methods

3.1 Case study context: Climate Services for Agriculture and "My Climate View"

The effects of climate change, including drought and other extreme events such as flood, fire, extreme heat, or greater rainfall variability, are expected to put Australia's agricultural industries and regional communities under increasing environmental, economic, and social pressure (Darbyshire et al., 2022; Howden et al., 2007). The Australian Government's Future Drought Fund (FDF) was established to help support Australian farmers and associated communities to prepare for, and become more resilient to, the impacts of future climate risks, including drought. The CSA program contributes to the FDF's objective to provide better climate information, which will help farmers prepare and adapt to future climate conditions and therefore improve drought resilience in Australia. The first phase of CSA was a $29 million program of work during 2020–2024, which focused on co-developing the online tool "My Climate View" to help Australian farmers and farm advisors better understand the future climate risks and opportunities they face over the next 50 years.

The My Climate View brand was released in 2023, with earlier protypes called "Climate Services for Agriculture." My Climate View provides localized and contextualized, commodity specific climate information, including historic weather data, seasonal forecasts, and multi-decadal projections of future climate. The online dashboard allows users to select their location and commodities, and then explore commodity-specific information about the future climate in their area. They can also explore more general climate information for their chosen area, as well as modify certain commodity specific variables, such as growing season length or extreme heat thresholds. Other Australian climate service products currently available focus on either a specific locations or commodity groups. My Climate View provides national scale climate information, tailored to 22 different agricultural commodities, ranging from tree crops such as almonds and apples, grains such as wheat, barley and canola, as well as livestock such as beef, sheep and pork. More commodities are being progressively added as the tool is updated.

Extensive research and engagement activities contributed to the design and development of My Climate View, including demonstrations, webinars, field days and training sessions, usability tests, visits with Indigenous landholders on Country, as well as qualitative interviews with farmers and farm advisors (Snow et al., 2024a). A dedicated Indigenous engagement team liaised with Indigenous agricultural businesses and community groups to seek feedback on CSA. These discussions highlighted the potential for Map View versions of My Climate View to better support custodians of land areas larger than typical farms. While beyond the scope of this paper, indigenous engagement continues to be an important focus of CSA (for further details, see Snow et al., 2024a). The FDF's Drought Resilience Adoption and Innovation Hubs (Drought Hubs) have also been an important focus of CSA's research and engagement activities. Established across Australia as part of the FDF program, the eight Drought Hubs create a network of local and regional stakeholders focused on developing, extending and encouraging the adoption and commercialisation of drought resilient practices and technologies (Australian Government, 2024a,b). Drought Hubs support farmers and communities to prepare for drought by providing access to innovative tools and technologies, through practical extension and adoption activities that meet local needs. The Drought Hubs therefore have the potential to contribute to improved drought resilience, including through promoting locally led transformational change needed for Australia's agricultural sector and regional communities to adapt to future climate conditions.

3.2 Participant recruitment and data collection

This paper synthesizes findings from semi-structured, qualitative interviews conducted with 52 farmers and 24 advisors in 2021 and 2023, as part of CSA's social science research on farmer-advisor interactions (see Table 1).

Participants were invited through informal networks, previous engagements with My Climate View demonstrations, field days and events where they registered their interest. In the case of advisors, our selection criteria included all participants who identified as performing a role which provided advice to farmers. Although the term advisor includes both formal and informal providers of information and advice, the advisors we interviewed were all professional advisors, meaning those who provide advice in a professional capacity in a range of private and public sector organizations. In 2021, we interviewed 25 farmers and six agronomic advisors from a range of commodity types and regions across Australia, exploring farmer and advisor perceptions on how climate information can help with on-farm decision-making, and how the CSA prototype could potentially help with accessing this information. In 2023, we conducted further interviews with 27 farmers and 18 advisors from across Australia. We explored in more detail farmer-advisor interactions and the role of different types of advisors as key partners in achieving adoption of My Climate View at scale. Of the 18 advisors we interviewed in 2023, eight were agronomic or industry-based advisors, while ten were based in public sector organizations that receive government funding to provide

TABLE 1 Interview participant summary by year, role, gender, and number of participants.

Year	Participant roles and interview codes	Participants by gender	Total participants
2021 (R1)	Farmers (F)	Male: 14; Female: 11	25
	Agronomic and industry advisors (A)	Male: 5; Female: 1	6
2023 (R2)	Farmers (F)	Male: 21; Female: 6	27
	Agronomic and industry advisors (A)	Male: 3; Female: 5	8
	Natural resource management extension officers and knowledge brokers (AE)	Male: 7; Female: 3	10
Total farmer interviews		Male: 35; Female: 17	52
Total advisor and extension interviews		Male: 15; Female: 9	24
Total interviews			76

information and advice to land managers on natural resource management and drought resilience. Eight of these advisors were affiliated with several of the Drought Hubs across Australia. However, to maintain participant privacy we have not identified their specific organizational affiliations.

Interview participants were recruited with the assistance of our research partner FarmLink, or through existing contacts among the research team. This research was approved by CSIRO's Social and Interdisciplinary Science Human Research Ethics Committee (approval number 001/21). The interviews were on average 40 min in duration and were conducted via phone or video conferencing software. The interview questions covered four main sections: participant background; current use of climate information to help with on-farm decision-making; feedback on the CSA prototype (in 2021 and early 2023) or My Climate View (in late 2023); and thoughts on how climate information could help with adapting to future climate conditions.

3.3 Data analysis

Both rounds of interviews were audio recorded and professionally transcribed. We used the qualitative data analysis software QSR NVivo® to aid the coding, analysis, and management of the data. Interview transcripts were analyzed using "bottom up" and iterative coding followed by thematic analysis, resulting in a hierarchical coding structure of themes and sub-themes through multiple rounds of coding. This paper focuses specifically on the subset of themes relevant to interactions between farmers and advisors.

4 Results

Our study explored the role of advisors as key intermediaries within the My Climate View interaction space, including concepts of trust, shared learning and scaling opportunities within farmer and advisor interactions around understanding climate information and exploring climate adaptation options.

4.1 Advisors as key intermediaries within the My Climate View interaction space

The role of advisors as key intermediaries was a recurring theme in our interviews. We interviewed advisors from private agronomic services and industry-specific advisory organizations, as well as advisors with a focus on natural resource management (NRM) extension. Many of the NRM extension officers and knowledge brokers that we interviewed were based within several of the Drought Hubs across Australia, which are part of the FDF initiative. As these advisors explain, their primary role in the Drought Hubs involves sharing information and facilitating connections between researchers and farmers:

> So obviously you become that kind of connection point for the Hub activities… There's a lot of programs and opportunities and grants and…it's just really trying to provide that role of connecting…[and] making sure that other people are aware of those programs. And then, obviously, if there's landholders… wanting to get involved in something, we can also point them in the right direction. (R2-AE8)[2]

> And our role is really to connect researchers and producers, and producers with researchers. So, both ways. …We tend to be more working with other farming systems groups, which are groups of producers or researchers going down the way, taking research to producers. (R2-AE12)

Private sector advisors, such as agronomic and agribusiness consultants, as well as agricultural input providers or resellers, were also identified as key influencers on farmer decisions:

> Those people that influence decision making on farms, so they tend to be the agronomists, the farm business consultants, the resellers, they have a big say in what farmers do. …But the big three are the private consultants, the resellers and the business consultants. (R2-AE11)

Given their importance in sharing information and brokering connections within their social networks, advisors have an important role in the My Climate View interaction space. For instance, advisors can play a key role in connecting people interested in climate information with My Climate View:

> But obviously having the platform that CSA has there, again, it's that kind of connecting people, so that if you do have somebody, somebody who's interested in looking into that sort of stuff, you can point them in the right direction …And I would say, we have a number of … extension staff that go out on property, I mean, you want that sitting in the back of everybody's head that they can show it off to somebody if that suits their situation. (R2-AE8)

The advisors we interviewed identified various ways that My Climate View might help them to provide advice to farmers on climate related decisions, such as strategic or investment planning, natural resource management planning, broader land management decisions, or succession planning. Some advisors described how they had already shared outputs and data from My Climate View in reports, presentations, or analysis, to help communicate climate information relevant to their region:

> And I found that [CSA prototype] really interesting, and I made sure to share some of those graphs… [at a symposium] last year. And I did highlight that our region is warming up and then you can find more information of different industries and all that on the website. (R2-AE3)

Most advisors focused on the potential for My Climate View to support long-term, strategic decisions, given its focus on future climate information:

2 Interview participants are categorized according to the interview round (i.e., R1 for 2021 interviews and R2 for 2023 interviews) and role (i.e., A=agronomic/industry advisor interviews, AE=extension and knowledge broker interviews, and F=farmer interviews).

> Well, I think mainly those long-term decisions obviously, in terms of investment, so if I'm investing in long term things, is this going to impact it? Because some of these long-term decisions, if I'm looking at somebody buying a farm, that's at least a 20-year decision or more, so we need to understand how climate might impact that. …I guess in some ways, it would help justify some of those shorter-term decisions in machinery investment. And what enterprises we should be looking to incorporate within our farming system. (R1-A2)
>
> People wanting to trial things. And it might be complete changes in what people are doing. …I can see it as a great tool for decision making and future planning. (R2-AE13)

Advisors also identified the potential for My Climate View to help to "stress test" longer-term, strategic decisions (e.g., investment decisions, or crop changes) for future climate scenarios:

> So, the idea is…that I have a good base for understanding how the business has performed over the last five or 10 years, I then use that information to derive an average scenario, and then I'll look at stress testing that scenario. So, if we're looking to buy a property, or looking to have a big investment in machinery or something like that, then I'll make sure that they're year in year out, I call it the year and year out situation, will work. If the situation works, then it's got one tick. If the balance sheet can afford it, it's not going to put them in a very risky position in terms of too much debt, that sort of thing, you get another tick. And then I stress test it for, let's say we have a drought, let's say we have a very poor year, what say we have two poor years? How does that look, does the business still survive in that sense? (R1-A4)

Similarly, advisors also described how they saw potential for integrating My Climate View into their extension and advice activities related to farm planning and climate resilience, as well as broader natural resource management planning:

> …I thought your tool [My Climate View] was very helpful in how I am intending to promote technology like this or resources to be incorporated into farm planning to be more climate resilient (R2-AE13).

Several of the advisors we interviewed identified the Farm Business Resilience Plans as an opportunity to integrate My Climate View into on-farm climate adaptation decisions:

> …at the more farmer level, I think that all comes back to integration with farm plans and my understanding is that a lot of farms are now embracing doing plans and incorporating resilience into it, just that longer term thing, I think. (R2-AE7)

Our interviews therefore highlight the way that advisors are key climate information intermediaries within the My Climate View interaction space, providing a range of advice and support to farmers on different types of decisions, including strategic and operational planning, investment, risk, and succession planning. Advisors provide information and support in diverse ways as well, in reports, in one-on-one conversations, through group presentations, which also scales their impact, making them key partners in scaling adoption within the My Climate View interaction space.

4.2 Trust and climate information intermediation in the My Climate View interaction space

Our interviews with both farmers and advisors demonstrated how trust in advisors is a key feature of farmer-advisor interactions in agricultural advisory networks, including climate information and advice networks. For instance, growers and grower groups trust advisors to provide targeted information and support:

> The local grower group…they work closely with us…when it comes to extending new information to growers. If the growers within their membership and their executive, if they highlight a priority that they think, well then they will discuss with us, well they want to look at this, can you help us do that? (R2-A15)

Similarly, the farmers we interviewed reinforced the trust that farmers placed in advisors as a source of information and support. For instance, farmers described the many ways their trusted advisors provided support for on-farm planning and decision-making:

> …one thing I've learned is to get professional advice and we use an agronomist who is a scientist and if we moved into a new crop, I'd be getting him to look at the soil, look at the climate, and give me advice on what crops are going to be the most productive on the basis of what he looks at rather than just launch into it. (R2-F15)
>
> She's [advisor] part of the program and we'd be talking about what we're planning with her and that sort of thing. And she would be indicating if there's any problems or whatever. I mean, yeah, she doesn't come along and say 'you must do'. I mean it's really an advice thing. (R2-F19)

Our farmer interviews also highlighted the important role for advisors in helping farmers to access and interpret climate information. In our first round of farmer interviews, concepts of trust and the complexity of climate information were key themes. Given the complexity of climate information, we found that trust in this context often relates to participants' perceptions of accuracy of the climate information. As this farmer explains, farmer's trust in climate information is often influenced by their assessments of the trustworthiness of the information source:

> Well, I suppose it comes down to how much you trust information that comes to you. So, I've got a large degree of trust in what we get from the Bureau [of Meteorology]. So, I suppose if you read something that's a bit out there, they get back to the Bureau and see what they say. (R1-F18)

Our interviews showed that farmers are unlikely to act on climate projection information alone. Rather, they synthesize it with a wide range of other information, including both external advice and local knowledge. This is because the information needs to be put in their specific local context, and every context is different. As a result, farmers described how they triangulated a range of information sources, including different forecasting apps and services, their own experience and intuition, and advice from trusted and long held relationships with peers, networks, and/or advisors, to help make sense of climate information and how it could apply to their situation.

Trust is also relevant to the question of whether farmers and advisors saw potential for My Climate View to help inform future climate adaptation decisions. Our second round of farmer interviews also revealed a range of different levels of trust that farmers placed in My Climate View as a source of climate information. Some farmers trusted and valued the information that My Climate View provided, finding it useful as: evidence in lobbying (R2-F22), as basis for future water availability modeling (R2-F23), to inform ongoing deliberations around whether to invest in indoor growing (R2-F18, F25), in considering orientations of future vine planting, canopy maintenance regimes (F26) and validation of previous decisions (R2-F18, F22). Some farmers said that they did not completely trust the information, but still intended to use it again, taking the projections with 'a grain of salt' (R2-F1, F4, F26), or reasoning it was "better than my guess" (R2-F8).

In contrast, some farmers trusted the information from My Climate View but did not intend to use it. Usefulness and intention to use were moderated by factors such life-stage, with some farmers (R2F15 and R2F20) who were looking to exit agriculture in the coming years trusted the information but had no intention of using it. Furthermore, other farmers (R2-F5) interpreted the future climate information as beneficial to their crops, which they perceived as reducing the likelihood of them needing to engage with My Climate View further. The range of farmer responses illustrates the challenges associated with using long-term climate information for on-farm decisions.

The farmer responses to My Climate View also reveal the breadth of opportunities for advisors to work with farmers to explore different scenarios for how information about future climate could inform on-farm decisions, including ways that advisors could tailor their advice to suit the needs of different farmers. For instance, farmers described how their agronomist might be able to use My Climate View to help inform on-farm decisions such as new crops:

> If I get a proper agronomist showing I want to grow mung beans or soybeans through the harvest season in the Burdekin and what best time is it for me to plant? They can get on your website, the CSA website and plan, and tell you what variety to plant, when to plant because it gives you enough of an indication. (R2-F17)

The role of advisors as trusted climate intermediaries means they are important partners in scaling adoption of My Climate View, as these advisors explain:

> I think we have to do it too, as [local organisation name omitted], because the thing with adoption is trust. So, if you're just coming in from nowhere and saying, "trust me", that takes effort and time. But, if you work with someone they already trust, I think the adoption may be a bit better. (R2-AE17)

> I think initially it [My Climate View] would probably be adopted by the extension officers first and then when they sit down with the farmers and show them things, I think you will start to pick up some farmers along the way who are interested and think, what's that? Can I use that? So yeah, I think a bit of both, but it might be a process where extension comes first and then the farmers themselves. (R2-AE7)

> I think that the information that's displayed on the Climate Services for Agricultural website is very handy to know. …I definitely would be interested in learning a bit more about it, also how to navigate it because I would then try to explain that to the graziers. I would then try and go about my own system of knowing how the graziers think and how would be the best way to explain the data to them in a way that would make sense. (R2-AE5)

Given their role as trusted climate intermediaries, the advisors we interviewed highlighted the importance of making sure My Climate View was embedded within existing programs and local groups:

> The first impression [of the CSA prototype] is that there's a lot of really interesting medium- and longer-term data there, and it'll be really great if we linked into the existing support services…and that this information will be able to really support other services and other services will be able to help the CSA platform too. And it's much, much further down the track, but it would be really useful I think if the CSA were to partner up with very broad extension strategies so that it was embedded within them just to make it quite seamless. (R2-AE6)

> That's one of the approaches is working with those groups. It's particularly the farming systems groups, I think. Yes, some of those farming systems groups are really progressive, and they are wanting to, at this point in time, think about and even have demonstration areas or sites of what a farm might look like, or need to look like in that time. (R2-AE12)

Therefore, trust is an important factor within the My Climate View interaction space, both in terms of how advisors themselves trust the climate information it provides, and how they mediate trust in new forms climate information with farmers, which is an important part of scaling adoption. Advisors can help to achieve scale through introducing climate projections to a broad range of local networks and contexts, even non-agriculture ones. Advisors can therefore play a key role in supporting discussions about how to interpret and contextualize the information from My Climate View, which is a vital part of making such information accessible and useful for supporting on-farm decision-making.

4.3 Learning and scaling within the My Climate View interaction space

Although many advisors could see ways that they might use My Climate View in their interactions with farmers, the complexity of doing so meant that most advisors we interviewed noted that additional support and training would be valuable. For example, this advisor discusses the need for further training before they would feel confident using My Climate View with a farmer:

> I probably at the moment wouldn't show them the [CSA prototype] website. I might show it to them and introduce it to them, but I just know that as it is, I feel like I would be lost if I tried to explain how it worked… (R2-AE5)

Providing support to advisors is therefore an important component of the My Climate View adoption and engagement strategy, which includes various awareness raising and training activities with farmers and advisors across Australia. The value of peer learning was also highlighted in both farmer and advisor interviews. For example, these advisors emphasized the importance of creating opportunities for peer learning for farmers in the context of supporting on-farm climate adaptation:

> …the big thing that we've found, is case studies and people talking about what they're doing…is what our members take home and think, "Oh, I couldn't do everything he's doing because—but I might be able to do this little bit of it." So, yeah, I think that peer group thing is what they mainly learn from. …I think that's how farmers learn, from each other, and the social side of it and there's that support…like, we were having coffee mornings on Zoom just to keep the connection and people being able—you know, "It's not just me" (R1-A3)
>
> Peer-to-peer learnings are probably the biggest out here. If they see, "Oh, mate, how did you know that," and they say, "Oh, well, I looked at this." I think that's probably the only way we can start getting that information and training out there as producer groups training. (R2-AE9)

Similarly, one of the advisors who attended a training session on My Climate View suggested that creating a space for ongoing peer learning among advisors would be valuable for supporting scaling of My Climate View:

> And you could have engaged the people who did the workshop together so that then they form a small, what would you say, a peer-to-peer group, which then can talk to each other a bit more. The opportunities for connection with this could enhance its uptake as well. (R2-A17)

The need to create opportunities for shared learning within the My Climate View interaction space reinforces the way in which the co-production of climate services should be underpinned by a partnership approach that builds climate resilience within local contexts, rather than a simplistic transfer of technology approach.

5 Discussion

Using the conceptual framework of an agricultural innovation interaction space, our CSA case study illustrates how advisors are valuable intermediaries, performing many different types of intermediation in the development of multi-decadal climate information services, since they can help to ensure the information is accessible and useable at the farm scale. This is vital to ensure that climate information is able to be used on-farm to support longer-term decisions about climate adaptation (Andrieu et al., 2019). The My Climate View interaction space is characterized by multi-stakeholder relationships, spanning both the R&D networks (i.e., the CSA project team and partners within the broader FDF initiative) that are developing the My Climate View tool, and the Farming System networks, involving key partners in the co-production of My Climate View and engagement with the broader CSA program.

Within this interaction space, advisors play a key role as trusted climate information intermediaries, which means they are valuable partners for scaling adoption of My Climate View. Interactions between farmers and their trusted advisors are fundamental in shaping long-term on-farm decisions (Haigh et al., 2015; Prokopy et al., 2017; Prokopy et al., 2013). We found that advisors bring together experience across multiple farming and local contexts, and often their own personal situation involves farming, so they can represent a broad perspective of farms and understand how climate information may impact different farm contexts in different ways, and the range of actions that can be undertaken in response. As illustrated in Figure 2, the different intermediation roles played by advisors are: (1) key networkers for sharing information; (2) key mediators of trusted information; and (3) key knowledge brokers for new forms of digital information within the CSA co-production interaction space. These farmer-advisor interactions are a catalyst to long-term climate information being used at the farm scale to inform longer-term decisions about climate adaptation.

5.1 Advisors are key networkers for sharing information

Our case study illustrates how advisors can intermediate in different ways, including network-building and brokering for knowledge exchange (Bäumle et al., 2023; Hernberg and Hyysalo, 2024; Moss, 2009). Within agricultural innovation interaction spaces, social networks are important to share expertise, and to ensure that advisors can keep up-to-date and learn from, and with, their peers. This is particularly important as knowledge proliferates online and advisors need to synthesize complex or competing information, which is often the case for climate adaptation (Cradock-Henry et al., 2020). Social networks also feedback into foundations for personal or relational trust (Carolan, 2006). If many social connections (such as friends, family, neighbors, and trusted advisors) have similar views, that may support information to be trusted. In terms of climate change, social networks may underpin climate denial as well as climate activism, with agriculture often highlighted as a cohort that includes climate skeptics (Robertson and Murray-Prior, 2016), but there are signs momentum is shifting through groups such as Farmers for Climate Action (Hinkson, 2022), and younger generations. However, climate skeptics and activists alike can still find benefit in different uses of the climate information in CSA, such as looking at trends or historical data without focusing on future projections or the causes of change (Snow et al., 2024b).

Advisors do more than just share information, they often need to adapt information to share with different types of networks within the interaction space, in different forms. The different forms of interaction can range from verbal conversations one-on-one with

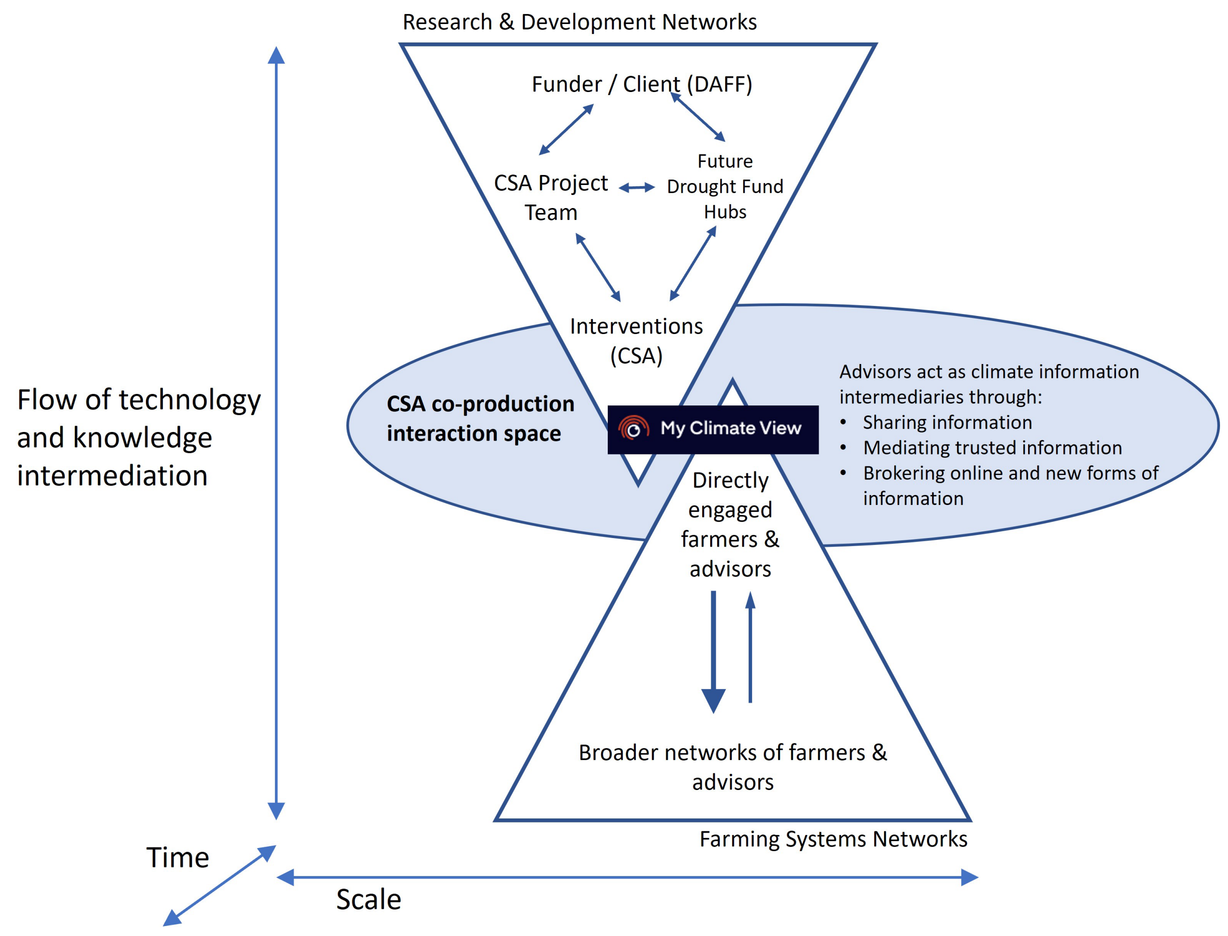

FIGURE 2
CSA and "My Climate View" co-production interaction space, adapted from Hermans et al. (2023, p. 8).

farmers, or in groups, to written interactions in emails, or through newsletter updates. This means that advisors are an important mechanism to reach different types of people, with different types of messages about climate. Through this intermediation process of configuration, advisors create brokered knowledge, which helps to make information useful to different actor groups (Meyer, 2010). Given the complexity of climate information, we found that advisors provide valuable support for interpreting the practical implications of future climate projections for on-farm decisions, such as providing advice on suitable commodities considering future climate conditions or helping to interpret what a possible change in future climate conditions (such as increased temperature or decreased rainfall) means for specific commodities in different regions. Advisors can also help with on-farm strategic planning, through initiatives such as Farm Business Resilience Plans (Australian Government, 2024c), trialing new practices and informing strategic investment decisions, all of which can be informed by better climate information. Advisors therefore add value by adapting information to local contexts, enabling the translation of climate information into action on-farm. However, advisors must be supported by their organizations to keep up to date and have access to information, as well as encourage information seeking and sharing and thinking about risks and opportunities (Lemos et al., 2014).

5.2 Advisors are key mediators of trusted information

As trusted and credible sources of information and support, advisors can help to bridge the gap between climate science information and on-farm decisions (Haigh et al., 2015; Prokopy et al., 2017). Agricultural advisors often (but not always) have longstanding relationships with their clients, share their local knowledge and social connections and are much more trusted as a result (Ingram, 2008; Juntti and Potter, 2002). In agriculture, studies have explored the development of trust between farmers and advisors and found that experience and trust are interconnected (Sutherland et al., 2013) and trust is often earned slowly (Hilkens et al., 2018). Trusted advisors may also be called upon to support farmers outside of technical decisions (Cook et al., 2021). The potential impacts of climate change on agriculture can be overwhelming and distressing for some people, but a trusted advisor can support farmers' wellbeing by making practical suggestions for action and being a source of connection and understanding (Hammersley et al., 2022). How climate change will impact individual farms is highly uncertain, and climate projection tools like My Climate View provide future climate information that needs interpretation to be applied to specific decision contexts while at the same time considering the inherent uncertainty of these projections (Haines, 2019;

Lemos et al., 2014; Robertson and Murray-Prior, 2016). Such uncertainty can affect the uptake of new technologies (Eastwood and Renwick, 2020), including climate services such as My Climate View. Advisors can help with navigating this complexity and uncertainty, including providing advice on which of the different climate service tools available could be most useful in different contexts (Haines, 2019). Therefore, the trusted roles of advisors are vital to allowing frank discussions around uncertainty, personal circumstances and practical ways forward. In some cases, no action may be the best course to take, but looking ahead and thinking about possible impacts and planning ways to prepare is important. Advisors can be critical in encouraging early adaptation planning and are often willing to give advice based on climate information despite uncertainty (Lemos et al., 2014).

For advisors to trust climate information enough to use it in their own work and planning decisions and/or recommend it to others, it helps if they are part of the development of the information so they can better understand the information itself, as well as provide feedback on how to make this information more useful and accessible (Fleming et al., 2023). Partnering with developers of climate information helps advisors to learn what information is available and how it could be used while having input into what information exists and how they interact with it. If advisors trust and use the climate information regularly, over time this embeds the legacy of the CSA program, and the practice of considering long-term climate projections, into the Australian agricultural innovation system. Such an approach to incremental technological transformation of a sector helps to achieve impact and supports transformational change on-farm, without strictly predefining what that impact is or could be. It is also worth noting that the Australian FDF initiative has provided an institutional incentive for advisors to engage with climate information, which contrasts with barriers reported elsewhere to advisors trusting and using climate information (Prokopy et al., 2013).

5.3 Advisors are key knowledge brokers for new forms of digital information

Farmers have different levels of digital literacy, and different capacities to access and use digital information, due to factors such as access to and speed of internet connections, serviceability, and cost discrepancies across rural–urban divides (Fielke et al., 2020; Marshall et al., 2020). This variability means that advisors are key knowledge brokers within the My Climate View interaction space, facilitating connections between climate information developers and farmers, feeding key insights of relevance and interpretability to developers, and insights and recommendations to farmers. Other studies have highlighted that open discussion and dialogue between farmers and advisors is an important part of building confidence in such online climate information tools (Malakar et al., 2024b). Advisors can therefore be critical conduits for farmers to access information online and help bridge the "aspirations-impact" gap common to climate information, namely the tendency for climate information not to be adopted or considered in decision making processes (Findlater et al., 2021). Understanding the role that advisors can play allows those developing online climate services to be able to work more effectively with specific advisor groups (Haigh et al., 2015).

Recognizing the role of advisors as key knowledge brokers within the My Climate View interaction space also highlights the importance of moving beyond a focus on individual farmer decision-making, to better understand the wider network of stakeholder relationships that are engaging with My Climate View (Hermans et al., 2023). This in turn underscores the importance of providing advisors with the training and support they need to be able to have confidence in using My Climate View in their interactions with farmers and even other natural resource management stakeholders. Appreciating the complexity of farmer and advisor interactions within the My Climate View interaction space emphasizes that the potential impact pathways or uses of My Climate View are potentially more diverse than initially imagined, and could extend to other sectors beyond agriculture, including broader natural resource management planning, or even educational settings, such as climate education in schools or universities. The non-linear nature of adoption of climate information emphasizes the importance of designing online climate services in a way that is aware of and responsive to the needs and connections between different types of users of climate information, rather than just focusing on either famers or advisors (Rijswijk et al., 2019; Snow et al., 2024a). Many individuals can play an advisory role, even if they are not employed as farm advisors or agronomists. This means that thinking about agricultural advisors broadly, and the institutional arrangements that underpin these interactions and relationships is also important. Engaging broadly to develop new climate tools can therefore be beneficial to build trust and collaboration and ease integration of climate tools into institutional processes (Lemos et al., 2014). Integration into social and institutional processes is a key part of scaling adoption.

6 Conclusion

Advisors play a central role in scaling climate services and supporting adaptive decisions. This recognition of the importance of farmer and advisor interactions within the My Climate View interaction space has helped to shape the development and engagement activities within the CSA program. Interactions between farmers and their trusted advisors are fundamental to helping farmers to better understand what future climate conditions might mean for their specific commodity and regional contexts. These farmer-advisor interactions are therefore a catalyst to multi-decadal climate information being used at the farm scale to inform decisions about climate adaptation. The co-development and scaling of My Climate View is an ongoing journey that will take years. Reflecting on how My Climate View fits within a "co-production interaction space" highlights the way that collaborative relationships need to be actively fostered to encourage on-going learning, collaboration, and knowledge brokering networks, to encourage and guide the changes in practice over time that are needed to collectively adapt to future climate conditions. The next phase of the CSA program will need to continue to maintain ongoing partnerships that are needed to continue to co-develop scaling of information, sharing learning and implementing action (Schut et al., 2020). While My Climate View is not a transformational technology on its own, it can be part of a conversation between farmers and advisors, enabling them to explore and discuss future climate conditions and consider implementing strategic climate adaptation measures that are tailored to specific, local contexts. Therefore, when climate services such as My Climate View are developed in a partnership approach and embedded within local advisory networks, they have the potential to support transformational changes on-farm that are necessary to meet the sustainability transition pressures that climate change presents.

Data availability statement

The datasets presented in this article are not readily available because of ethics conditions to protect the anonymity of respondents. Requests to access the datasets should be directed to emma.jakku@csiro.au.

Ethics statement

The studies involving humans were approved by the CSIRO Social and Interdisciplinary Science Human Research Ethics Committee. The studies were conducted in accordance with the local legislation and institutional requirements. The ethics committee/institutional review board waived the requirement of written informed consent for participation from the participants or the participants' legal guardians/next of kin because we obtained verbal informed consent at the start of interviews instead.

Author contributions

EJ: Conceptualization, Formal analysis, Methodology, Writing – original draft. AF: Conceptualization, Formal analysis, Methodology, Writing – original draft. SF: Conceptualization, Formal analysis, Methodology, Writing – review & editing. SS: Conceptualization, Formal analysis, Methodology, Writing – review & editing. YM: Writing – review & editing. GC: Writing – review & editing. RH: Writing – review & editing. LW: Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. This study was funded by the Australian Government's Future Drought Fund, administered by the Australian Government Department of Agriculture Fisheries and Forestry (DAFF), and the Valuing Sustainability Future Science Platform (VS FSP) at the Commonwealth Scientific Industrial Research Organisation (CSIRO).

Acknowledgments

We gratefully acknowledge the input provided by the CSA team and give particular thanks to the farmers and advisors who gave generously their time to share their experiences through interviews. We are also grateful to Sarah Clarry and Stephanie Dickson for helping us with interview participant recruitment. We acknowledge funding from the Australian Government's Future Drought Fund and the Valuing Sustainability Future Science Platform (VS FSP) at the Commonwealth Scientific Industrial Research Organisation (CSIRO).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 08 January 2025
DOI 10.3389/fsufs.2024.1493753

OPEN ACCESS

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RECEIVED 09 September 2024
ACCEPTED 19 December 2024
PUBLISHED 08 January 2025

CITATION
Dumas Y, Ubacht J, van Andel E and Keledorme LA (2025) Exploring the transition to agroforestry for smallholder farmers: a feasibility study for the Ashanti region of Ghana.
Front. Sustain. Food Syst. 8:1493753.
doi: 10.3389/fsufs.2024.1493753

Exploring the transition to agroforestry for smallholder farmers: a feasibility study for the Ashanti region of Ghana

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Smallholder farmers in the Ashanti region of Ghana face challenges due to shifts in climate patterns that have a significant negative impact on their crop yields. We conducted a feasibility study into the transition toward an agroforestry system by integrating trees and shrubs within crop fields. In this research, we adopted a complex systems perspective to analyse the institutional, social, and technical aspects that play a role in such a transition. By conducting in-depth analyses through three rounds of interviews and a Q-sort method with smallholder farmers in the Ashanti region, we mapped the most important challenges in transitioning to an agroforestry system. These pertain to: uncertainties in land tenure agreements, the absence of effective conflict resolution mechanisms, having no knowledge of and tools for maintaining trees, and the lack of financial resources for upfront investments. Based on our findings, we provide recommendations for the design of the transition process toward a comprehensive agroforestry system in Ghana. We recommend improving land tenure security and establishing conflict resolution mechanisms by polycentric coordination in which all stakeholders are involved for this essential institutional redesign process. To enable smallholder farmers to acquire the required skills and tools for tree crops, preferably a pilot plot for real-life demonstration is initiated. Financial resources for the smallholder farmers in the transition period need to be warranted, e.g., via the design of a carbon credit market. We recommend future research to explore the perspective and interests of chiefs/landowners in the Ashanti region who have crucial decision-making power through their land ownership.

KEYWORDS

Ghana Ashanti region, agroforestry, climate change, land tenure, agricultural training, carbon credits, livelihood assessment, sustainable agriculture

Introduction

Climate change represents one of the most urgent and pressing issues of our time, leading to significant shifts in climate patterns as a consequence of the increasing emissions of greenhouse gases (Shah et al., 2024). Human activities, including the expansion of the global economy and the reliance on fossil fuels, primarily drive these emissions. They trap heat in the Earth's atmosphere, leading to global warming. The consequences of climate change are observed across the globe, affecting the socioeconomic conditions of many communities, including those engaged in smallholder farming in the Ashanti region of Ghana, where agriculture contributes 21% of GDP (Ghana Statistical Service, n.d.).

The Ashanti region, located in the forest-savanna mosaic zone of Ghana, has a warm and humid climate due to its proximity to the equator. The climate is marked by distinct seasons. The rainy season, which occurs from April to September, is a season of abundant rainfall, encouraging lush vegetation growth. In contrast, the dry season, from November to March, is characterised by a lack of rainfall, reduced soil moisture, and an increased risk of forest fires. The region's heavy reliance on rain-fed agriculture makes it particularly vulnerable to the disruptions caused by climate change.

In recent years, climate change has intensified these climatic challenges, disrupting traditional weather patterns and leading to rising temperatures, erratic rainfall, and an increase in the frequency of extreme weather events (Comolli et al., 2024; Issoufou-Ahmed and Sebri, 2024). Such changes have had a significant negative impact on crop yields, thereby threatening the incomes and livelihoods of farmers who rely on consistent weather patterns for agricultural productivity. The erratic rainfall, in particular, has exacerbated water scarcity during the dry season, impeding the effective management of resources and the maintenance of soil moisture.

The combination of these climatic challenges and the region's growing population has resulted in a decline in agricultural productivity. In an attempt to address these challenges, farmers have increasingly resorted to the use of agrochemicals and monoculture practices. While these approaches may offer immediate solutions, they have been shown to contribute to the depletion of soil nutrients and water quality in the long term. Furthermore, the intensification of agriculture has had a detrimental impact on the region's biodiversity (Comolli et al., 2024; Dejene et al., 2022).

Consequently, those engaged in agricultural activities in the Ashanti region are experiencing increased feelings of insecurity. Income is unstable and dependent on erratic weather patterns, and current farming methods are unsustainable in the long term. Due to the limited economic resources available to them, these farmers are unable to invest in more sustainable approaches (Issoufou-Ahmed and Sebri, 2024; Acheampong et al., 2014; Darfour and Rosentrater, 2016).

One potential solution to these challenges is transitioning to an agroforestry system, which involves integrating trees and shrubs within crop fields in an agricultural method. Agroforestry has the potential to enhance soil quality, local climate conditions, pest and weed control, resilience to extreme weather, and water quality while also promoting biodiversity conservation (Addai, 2024; Comolli et al., 2024; Jose, 2009; Jose and Bardhan, 2012; Mbow et al., 2014; Vidhana Arachchi et al., 1997).

To implement agroforestry systems successfully, it is essential to gain an understanding of the local context, including climatic conditions, to ascertain their feasibility. This study assesses the potential for agroforestry in the Ashanti region, drawing on insights from interviews with smallholder farmers, experts, and stakeholders. Conducted in collaboration with the Farmerline Group, a Ghanaian company with a large network of connected farmers, this research explores the challenges and opportunities associated with adopting agroforestry practices in this region.

Theoretical framework

We adopted a complex systems perspective to obtain a comprehensive understanding of the complexities that affect implementing an agroforestry system. To this end, we employed a comprehensive methodology to investigate the complex interrelationships between the institutional, social, and technical sub-systems in the context of agroforestry adoption in the Ashanti region. This approach enables us to examine the multifaceted dynamics influencing its adoption process. By analysing these three subsystems that together form the agroforestry system, our objective is to gain a comprehensive understanding of the complexities that affect the system as a whole.

Before the empirical data collection and analysis, a literature review was conducted to establish a foundational understanding of the existing situation, examining the institutional, social, and technical subsystems. This initial phase was designed to ensure a comprehensive understanding of the current situation for smallholder farmers and to identify the key aspects that require investigation within the local context. Hence, in the following paragraphs, we start by presenting the findings from our literature review.

Institutional challenges

The term 'institutional system' describes the organised frameworks of laws, policies, governance mechanisms, and regulatory bodies that structure societal functions. These systems establish the rules and norms that govern the management of land, resources, and economic activities (North, 1991).

The most significant issue about the institutional system of Ghanaian farmers, as discussed in the current literature, is the land tenure system. A land tenure system is defined as a system of rules and regulations that govern access to land resources, including land ownership, access to land, and land exchange. In Ghana, the land tenure system operates within a complex framework characterised by legal pluralism, whereby there are various sources of formal and informal authorities governing land tenure (Obeng-Odoom, 2014). Two distinct land tenure regimes coexist: formal, documented, and registered agreements between tenant and landowner and informal, undocumented agreements. Presently, a considerable proportion of Ghanaian farmers are confronted with considerable land tenure insecurity due to the absence of formal land titles (Ibrahim et al., 2020). This absence renders farmers vulnerable to eviction and is a primary catalyst for numerous land tenure disputes (Kandel et al., 2021). Land tenure security is of critical importance to the livelihoods of Ghanaian farmers, as uncertainty in this area hinders long-term planning and restricts access to credit. This insecurity has a significant impact on farmers' capacity to invest and enhance the efficiency of their agricultural practices. Furthermore, it has important implications for adopting agroforestry systems, which require long-term investment. Since trees take time to grow and deliver value to farming activities, secure land tenure is essential for farmers to consider agroforestry as a sustainable option. Even fast-growing trees, such as cashews, take about 2 to 3 years to start yielding, according to a teacher at Ejura's agricultural college. Without long-term land security, farmers are reluctant to invest in agroforestry because the benefits may not be realised for many years (Interview Prosper Kugblenu, Ejura Agricultural College, November 1st, 2024).

Social challenges

The term 'social system' describes the network of relationships, cultural norms, and social structures that influence how individuals and communities operate. These systems shape the behaviours, practices, and decision-making processes within agricultural communities (Herder et al., 2008).

Approximately 70% of Ghana's farming population are smallholder farmers, a category of farmers defined by their limited land availability and resources (Peprah et al., 2020). Despite the gradual introduction of modern agricultural practices in the country, this transition has been significantly impeded by a dearth of financial resources, particularly among smallholder farmers (Darfour and Rosentrater, 2016; Acheampong et al., 2014). Their financial situation constrains their capacity to invest in new technologies and techniques that could potentially enhance their productivity and sustainability. Furthermore, traditional agricultural knowledge in Ghana is deeply embedded in cultural practices, which are frequently transmitted across generations (Aniah et al., 2019). Farming methods have remained largely consistent over time, with older farmers serving as the primary source of guidance for younger generations. According to Bonye et al. (2012), when faced with challenges, farmers typically seek advice from more experienced, older farmers rather than relying on formal education or external agricultural extension services. This reliance on traditional knowledge, while valuable, can also act as a barrier to the adoption of new, potentially more effective agricultural practices.

Technical challenges

The term 'technical system' describes the collective of tools, technologies, and methodologies that facilitate agricultural practices. This system encompasses the machinery, equipment, and scientific techniques that farmers utilise to effectively manage their land and crops.

The complexity of climate is a critical factor in farmers' decision-making processes, particularly in the context of Ghana, where the management of climate variability has become increasingly challenging. The phenomenon of climate change has resulted in an increase in temperatures and alterations to rainfall patterns, which have made it more challenging for farmers to predict and manage their agricultural activities (De Pinto et al., 2012; Ndamani and Watanabe, 2015). Projections for West Africa indicate that the future will be characterised by an increase in the frequency of droughts and a general trend towards drier conditions, which will further exacerbate the difficulties faced by farmers in the region (Sarr, 2012; Boko et al., 2007). Farmers in sub-Saharan Africa, including Ghana, frequently lack the capacity to adapt to these climatic changes, rendering them vulnerable to its impacts (Boko et al., 2007). In Ghana's Ashanti region, many farmers face barriers to adaptation due to limited formal education and resources, which slows the adoption of new practices (Interview Prosper Kugblenu, Ejura Agricultural College, November 1st, 2024). As indicated by the IPCC, the agricultural sector in these regions is particularly vulnerable to climate change, with the potential for significant adverse impacts on rural livelihoods and food security (IPCC, 2014). Furthermore, the continuous utilisation of conventional agricultural techniques has resulted in a sustained decline in soil fertility, exacerbating the challenges mentioned above (Nyasimi et al., 2017). This decline has resulted in a reduction in crop yields, which has led to a decline in income for farmers. Mason et al. (2015) observe that soil nutrient depletion has been a long-standing issue, intensified by the overreliance on conventional agricultural practices based on a monoculture approach. In response to these challenges, some farmers in West Africa have adopted conservation agriculture methods, such as crop rotation, to improve soil health. However, the increased use of agrochemicals while addressing immediate agricultural needs has contributed to further soil degradation (Kotu et al., 2017). These challenges highlight the necessity for implementing sustainable agricultural practices, such as agroforestry systems, to enhance resilience to climate change while improving soil fertility.

Methods

Following the literature review to analyse the current system and status of Ghanaian agriculture, we employed a qualitative case study approach, utilising in-depth interviews with farmers from the Ashanti region (see Figure 1) to gain a comprehensive understanding of the intricate local context pertinent to implementing the proposed agroforestry ecosystem. The Ashanti region has been selected as the focal area for this study due to its complex land tenure system, where much of the farmland is managed by traditional authorities. Additionally, it was chosen for its convenience, as access to the communities could be facilitated through Farmerline. The key aspects identified in the theoretical framework informed the development of interview questions for smallholder farmers in this region. Furthermore, these aspects were used to triangulate the interview

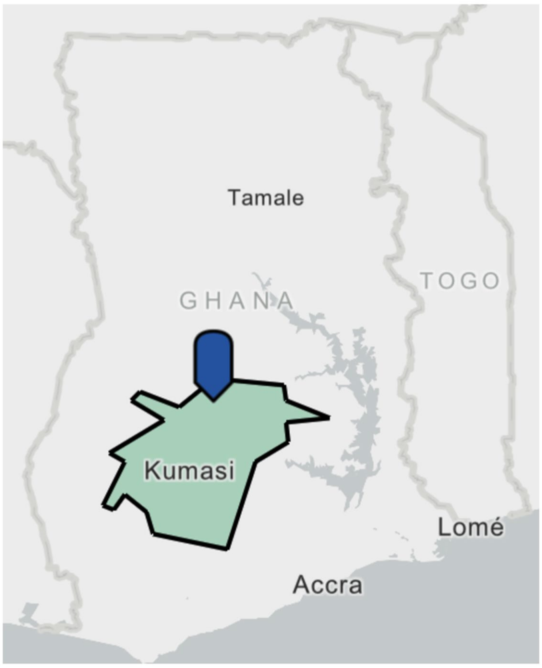

FIGURE 1
Map of the location of Ejura within the Ashanti region in Ghana, ~100 km north of Kumasi (map generated by ArcGIS).

findings, ensuring a nuanced understanding of the local context while accounting for the specific characteristics of Ashanti farmers.

The majority of the data and findings for this research come from the Ejura-Sekyedumase District to ensure a focused understanding of the local context. Located in the northern part of the Ashanti region, in the transitional zone of Ghana, Ejura experiences both high and low rainfall seasons, with temperatures reaching up to 38°C during long dry spells (Akowuah et al., 2015; Interview Prosper Kugblenu, Ejura Agricultural College, November 1st, 2024). This climate favours the cultivation of cereals and legumes, which are the main crops in Ejura, with around 70% of the population involved in their production in the region, and 85.6% in Ejura's rural areas—significantly more than the national average of 38.3% (Ghana Statistical Service, 2010; Ministry of Food and Agriculture, 2021). The size of the farming community in the region varies, with between 720 and 1,500 farmers actively involved in agricultural activities (Interview Prosper Kugblenu, Ejura Agricultural College, November 18th, 2024). Unlike other parts of the Ashanti Region, where tree crops such as cocoa, cashew and oil palm dominate, only 0.6% of farmers in Ejura engage in tree crops. Instead, the district's focus on cereal and legume farming is influenced by both its climate and land tenure system. Most farmland is owned by traditional families, which limits the long-term leasing of land to non-family members. In addition, many farmers in Ejura have migrated, 33.8% were not born in the region, from the northern regions of Ghana, where prolonged droughts drive them south in search of more favourable conditions. The majority of the working population –nearly seven in ten (69.6%)—are self-employed, with only 8.7% classified as employees. This confirms that most farmers are self-employed smallholders, farming relatively small plots of land for subsistence or small-scale commercial purposes, rather than engaging in large-scale industrial agriculture (Ghana Statistical Service, 2010). On average, each farmer cultivates around 2 hectares of land (Interview Prosper Kugblune, Ejura Agricultural College, November 18th 2024). This, coupled with the region's high poverty rate of 25% (Ghana Statistical Service, 2021), which is significantly higher than the national average, exacerbates the challenges faced by these farmers and limits their ability to adopt sustainable agricultural practices. Given these challenges, Ejura provides a challenging environment for agroforestry adoption, making it a suitable region for our study to explore the barriers to adoption.

The interviews were conducted in three distinct phases. The initial phase comprised a focus group interview conducted in the Ejura-Sekyedumase district. The focus group comprised 10 farmers from a specific farming community, which is characterised by a distinct hierarchical structure. This structure is governed by a three-person board comprising a leader, secretary, and treasurer. The leader and secretary participated in the focus group discussion. Farmerline selected the farming community based on its accessibility and willingness to participate. While this community was chosen based on its logistical suitability and the assumption that it could reflect broader regional trends, we acknowledge that the extent to which it is fully representative of other communities in the Ashanti region may be a potential limitation of the study. We reflect on this limitation in the conclusion section.

The second phase of the research involved eight in-depth interviews with individual farmers from a range of farming communities within the Ejura-Sekyedumase district. The farmers involved in the study exhibited a range of socioeconomic and agricultural characteristics (see Table 1). Six farmers were male (Farmers A, B, C, D, F, and G), and two were female (Farmers E and H). The sizes of their farmland varied significantly, ranging from 2 to 14 acres. Farmer A had the largest landholding (14 acres), while farmers F and H had the smallest (2 acres each), with an average of 6.88 acres. Most farmers grew maize and beans as their primary crops, with Farmer C also cultivating rice and Farmer H integrating mangoes alongside maize and beans. Experience with growing trees was unevenly distributed among the group. Farmers A, E, and H had prior experience with growing trees, whereas the other five farmers had no such experience. Additionally, there was a divide in agricultural training. Farmers B, C, and G had formal agricultural training, whereas farmers A, D, E, F, and H had no formal training. These characteristics highlight the diversity within the group, particularly in terms of gender, land size, crop variety, tree-growing experience, and access to agricultural education.

The objective of these interviews was to ascertain the extent to which the findings from the focus group reflected the broader community perspective. Furthermore, it was essential to ascertain the perspectives of farmers occupying diverse social positions, including those with smaller landholdings or female farmers, who might offer a more heterogeneous range of insights. The individual interviews provided a setting where participants could explore the topics more deeply. The farmers were selected straightforwardly, whereby those who expressed interest were invited to participate. In many cases, community elders facilitated the introduction to potential interviewees. While the farmers were eager to participate, it should be noted that this selection method may not fully guarantee representativeness across the broader region. We reflect on this

TABLE 1 Overview of the socioeconomic and agricultural characteristics of the eight interviewees.

	Farmer A	Farmer B	Farmer C	Farmer D	Farmer E	Farmer F	Farmer G	Farmer H
Gender	Male	Male	Male	Male	Female	Male	Female	Male
Produce	Maize, Beans	Maize, Beans	Maize, Beans, Rice	Maize, Beans	Maize, Beans	Maize, Beans	Maize, Beans	Maize, Beans, Mango
Land size (acres)	14	4	12	5	10	2	6	2
Experience with trees	Yes	No	No	No	Yes	No	No	Yes
Agri-training	No	Yes	Yes	No	No	No	Yes	No

limitation in the conclusion section. As is customary in the local culture, a small snack was offered to the farmers during the interviews.

In the concluding phase of the interviews, the primary objective was to elucidate the various characteristics of farmers that could potentially influence the implementation of agroforestry. To this end, a group interview was conducted with farmers cultivating various crops from different areas within the Ashanti region. This group interview took place during a training day at Kwadaso Agricultural College in Kumasi, Ghana, where farmers were gathered to learn about sustainable farming practices. Whereas the training did not specifically focus on agroforestry, it provided an opportunity to engage with a diverse group of farmers to gather insights relevant to their experiences and perceptions regarding sustainable agricultural methods. During this third phase of the research process, a Q-method group interview was conducted with two representatives from each of four different farmer groups, supplemented by input from a classroom of approximately 30 farmers from these groups. The objective was to ascertain the most significant factors to be considered when designing an agroforestry system. The Q-method is a qualitative research technique employed to study subjective perspectives and beliefs (Watts and Stenner, 2005). The method involves participants sorting a set of statements or factors related to a specific topic according to their personal viewpoints and has been applied in similar studies and contexts (Dugasseh et al., 2024). In this case, farmers were presented with a series of positive effects associated with agroforestry, such as improved soil health, increased biodiversity, and enhanced crop yields. They were then asked to rank these factors based on their importance or relevance to their agricultural practices. This method allowed us to uncover the underlying values and preferences of the participants, facilitating a deeper understanding of their perspectives.

This research was conducted with the assistance of Farmerline, a Ghanaian company that provides support to farmers in a variety of ways to enhance their agricultural production. Due to the extensive network of farmers connected to Farmerline, it was possible to recruit farmer participants for this study. In addition to facilitating contact with local farmers, Farmerline also facilitated access to a translator with expertise in the agricultural sector, ensuring that the farmers could provide the desired information.

Results

In this section, we present the findings from the interviews conducted with smallholder farmers in the Ashanti region, focusing on the key themes that emerged regarding the implementation of agroforestry. The results are organised according to the three sub-systems discussed in the literature review, namely the institutional, social, and technical subsystems. It is important to note that these interviews provide insights into the specific local context, which the current literature has yet to adequately address. Each theme is explored in detail to illustrate how these factors influence farmers' perceptions, experiences, and willingness to adopt agroforestry practices.

Local context—institutional system

The farmers indicated that operating within the existing land tenure system gives rise to considerable uncertainties regarding their future, largely due to informal transactions. Their farmland is officially owned by the local chief, and farmers hold annual leases with the chief, which are paid in cash. However, they have not received any official documentation that could reinforce their rights to cultivate the land. Consequently, farmers identified numerous instances where they could be prohibited from farming their designated plots and may be compelled to relocate to different farmlands in subsequent years. For those participating in this research, several factors contributed to the emergence of conflicts over land tenure.

The majority of farmers have experienced land disputes first-hand. A significant concern is the insecurity experienced by farmers cultivating land close to urban areas. The expansion of these zones frequently results in displacement from their farmland.

> *"During the construction of a prison a couple of years ago, many farmers had to leave their farmlands. They were informed on very short notice. This hinders many farmers from participating in long-term projects"—Farmer B.*

Furthermore, disputes frequently emerge from concerns related to land payments. Farmers reported instances where another individual could pay for a plot of land first, subsequently establishing themselves as the legitimate land farmer for that year.

The findings also indicate a notable lack of conflict resolution measures among farmers, particularly given their vulnerable position within the land tenure system. This absence of effective institutional mechanisms exacerbates their vulnerability, making it challenging for them to secure their rights and livelihoods in the face of ongoing disputes and external pressures.

The farmers also expressed uncertainty regarding the implications of planting trees on their farmland. While four out of eight of the farmers believed that the trees they planted would belong to them, three felt that ownership would need to be negotiated with the chief. One farmer observed that the trees would always belong to the chief. In the absence of certainty regarding ownership, farmers may be disinclined to adopt agroforestry practices, apprehending the possibility of losing both the trees and the prospective income they could yield. Furthermore, farmers noted that trees providing additional income could become sources of conflict. However, three farmers who had cultivated tree crops on their land for periods ranging from 5 to 15 years reported that they had not encountered any issues concerning the trees or the security of their land tenure.

> *"Planting trees could become a problem. Once trees start to provide revenue, the chief could make you farm another piece of land while taking the revenue from the trees, and you will have to start over again"—Farmer H.*

Furthermore, most farmers we interviewed disclosed that they had previously engaged in illicit logging activities. It was reported by half of the farmers that such activities were frequently instigated by one of the local chiefs. Most illegally logged trees are used for construction and roofing purposes, with teak being a common target.

> *"I was growing several trees on my farmland. When I went away for a week, the trees were gone when I returned.—Farmer A.*

It is also noteworthy that the responses provided by farmers to the same set of questions varied considerably. While they reported experiencing significant insecurity concerning land tenure and gave examples of both conflicts and a lack of effective conflict resolution mechanisms, they also indicated a lack of clarity regarding potential future developments. It appeared that there was a common sentiment of unease about the possibility of future issues. Yet, there was a lack of consensus on the specific nature of these potential challenges.

The third phase of the interview process was conducted with farmers from a range of locations within the Ashanti region, all of whom were engaged in the cultivation of different crops. The objective of this subsequent phase of interviews was to gain a more profound comprehension of the particular attributes of farmers that are perceived to contribute to their tenure insecurity. The findings indicated that farmers currently engaged in the cultivation of perennial crops experience a diminished level of tenure insecurity compared to farmers engaged in the cultivation of annual crops. Furthermore, some farmers who indicated that they were part of farmer associations observed that their tenure security was more secure than that of individual farmers who negotiated with chiefs over the farmlands.

The Ghanaian government, through its Lands Commission (Salifu, 2018), and non-governmental organisations have tried to enhance the number of farmers in possession of official land tenure documents, which serve as evidence of land ownership. Nevertheless, despite these initiatives, the farmers in the agricultural communities in the Ashanti region, who are the focus of this study, lack such documentation. Thus, the results of these initiatives are inconsequential for them. Interviews with representatives of a non-governmental organisation (NGO[1]) and Ghanaian government officials from the Ministry of Food and Agriculture revealed significant differences in tenure security between the various traditional areas.

In addition to Ghana's officially designated regions, such as the Ashanti region, there are also various traditional areas, which may be situated within a single region or extend across multiple regions. These traditional areas exhibit considerable variation. In larger traditional areas, high-ranking chiefs present a significant challenge for farmers or organisations seeking to navigate complex institutional frameworks. However, these frameworks may potentially facilitate the establishment of formal land agreements. Conversely, in smaller traditional areas, there is a dearth of institutional structures to facilitate the formation of formal land agreements. Nevertheless, it may be more straightforward for parties to engage with high-ranking chiefs in these areas.

Local context—social system

The lack of access to financial resources represents a significant challenge for farmers in the Ashanti Region. This issue was identified in the existing literature and confirmed by farmers during the initial two phases of interviews. It was reported that erratic rainfall and declining yields serve to exacerbate the financial difficulties already faced by these farmers. Many farmers indicated that they lack the financial capacity to make long-term investments. Instead, they stated that they often focus on raising sufficient funds to cover land rent to avoid further jeopardizing their land tenure security. Two out of eight farmers indicated that financial difficulties represent their biggest challenge. Furthermore, the farmers indicated that procuring superior inputs, such as seeds, is already challenging under the prevailing circumstances. This suggests that the sourcing of tree seeds for agroforestry practices can present a significant barrier to participation. Additionally, the financial constraints experienced by farmers limit their access to essential machinery and tools. The farmers noted that this lack of resources hinders their ability to engage in diverse forms of farming, as they lack the necessary equipment to maintain different agricultural systems, such as agroforestry.

The farmers indicated that their knowledge is primarily rooted in traditional farming practices passed down through generations. The transfer of this knowledge plays a pivotal role in agricultural practices within farming communities. Farmers are justifiably proud of their techniques and are keen to ensure the continued viability of their current methods. Furthermore, the crops they harvest are of great significance to the culinary traditions of their communities, with all the interviewed farmers emphasising the importance of these crops in the local food culture. Less than half of the farmers, three out of eight, have undergone formal agricultural training, with the majority depending solely on traditional methods. In discussions on alternative farming methods that could enhance yields, farmers indicated interest in exploring new concepts. However, many acknowledged their lack of knowledge regarding implementing these methods.

Despite an awareness of agroforestry principles, farmers remain uncertain about the potential benefits of this approach. Many had negative experiences with trees on their farmland, citing the overshadowing of regular crops and a subsequent reduction in yields. There is a general lack of knowledge about tree maintenance, and when combined with insufficient access to machinery and tools, farmers currently appear ill-equipped to sustain an agroforestry system. For example, farmers said that they were afraid to prune their trees at all for fear that pruning would result in a loss of crop.

Local context—technical system

The farmers reported that they are currently experiencing difficulties due to climate change, particularly due to the increased unpredictability of rainfall patterns, which affect their agricultural cycles. Over half of the farmers identified this as the most significant challenge they currently face. Another concern the farmers raised is increased pests and weeds observed in recent decades. They noted that current methods of pest and weed control—most farmers now rely solely on agrochemicals—are no longer effective, leading to a significant rise in pest and weed populations that cannot be managed with traditional techniques. Consequently, this increasing reliance on costly agrochemicals further strains their financial situation and is also a significant health and environmental problem as farmers have limited knowledge of the correct use of these chemicals, such as withdrawal and re-entry periods, resulting in traces of chemicals remaining in their produce, particularly in vegetables (Interview Prosper Kugblenu, Ejura Agricultural College, November 1st, 2024).

1 Despite our efforts, we did not receive a formal consent to disclose the name of the NGO in this article.

Design of an agroforestry system

Based on our findings, we explored how the implementation of agroforestry in the Ashanti region can be stimulated by formulating recommendations for changes in the institutional, social, and technical subsystems. These are presented in the following paragraphs.

Dealing with the institutional framework

The most significant institutional challenge identified in both the literature and the interviews with farmers in the Ashanti region is the lack of land tenure security, which prevents farmers from making long-term investments in their farmland. The lack of assurance that they will be able to continue farming the same plot of land in the future acts as a significant barrier to the adoption of agroforestry practices. The initial interviews revealed that farmers lack a unified understanding of how transitioning to agroforestry would affect their tenure security and are uncertain about the implications for land ownership. Additionally, there is a lack of effective conflict resolution mechanisms to manage potential disputes.

In the context of initiating an agroforestry project with smallholder farmers, it is critical to consider the farmers who will be eligible to participate. Several factors are of significant importance when selecting Ashanti farmers for participation. These include the farm's proximity to urban development, the currently farmed crops, and the traditional area in which the farm is located.

The optimal farmer is situated in a rural area, far from urban areas, to ensure that their farmland will not be utilised for urban or infrastructural purposes in the near future. It is preferable for the farmer to have experience with tree crops rather than annual crops, as the chief is already aware of the farmer's intention to cultivate the land for an extended period. In smaller traditional areas, it is more straightforward for farmers to obtain permission to farm the land for a longer period from a chief who is in a position of sufficient authority to grant such a request. It is of the utmost importance that the project be presented to the chief first, as informing the farmers first can potentially lead to misinformation about the project reaching the chief, thereby jeopardising the project's potential for success.

Subsequently, other farmers can be included in the process once there is more understanding of the effects and risks associated with farmers participating in an agroforestry project. In the current era, the absence of formal land documents and the lack of progress by the Ghanaian government in enhancing tenure security has created a highly challenging context for farmers in the Ashanti region. For farmers engaged in or interested in pursuing agroforestry practices or for organisations seeking to establish such projects, the current lack of effective and efficient solutions to address this issue represents a significant hurdle.

Designing the agroforestry system

To guarantee the willingness of farmers to adopt agroforestry practices, it is imperative to design a socio-technical system that integrates the technical aspects of agroforestry with the social system, which encompasses the farmer's knowledge, culture, and financial capital.

In the third phase of interviews, farmers indicated that the primary motivation for transitioning to agroforestry practices is the potential for increased harvests from tree crops. This was also identified as a key factor by seven out of eight farmers during the initial interview round. The selection of tree species influences the success of an agroforestry system, but farmers may prefer other tree species than the optimal selection for obtaining additional agroforestry benefits. A subsequent point for consideration when evaluating the potential benefits of an agroforestry system is the importance of intercropping trees with existing crops. During the interviews, the farmers expressed concerns about intercropping, citing the potential for the trees to overshadow their crops and negatively impact the current yields. Seven farmers indicated a preference for cultivating trees on a dedicated field. Additionally, Farmer H, who already cultivates mango trees, expressed willingness to engage in intercropping. Their concerns show that the farmers lack the requisite knowledge on tree maintenance, such as the importance of thinning, trimming, and pruning. This type of maintenance is not typically included in their traditional agricultural knowledge base. Consequently, the system should be designed in such a way as to ensure that farmers are satisfied with the tree selection while also taking into account which trees are suitable for the Ashanti region.

Interviews conducted with the Ghanaian Ministry of Food and Agriculture and the Environmental Protection Agency revealed that the most promising tree species for agroforestry in the Ashanti region are mango, cashew, and moringa trees for farmers cultivating annual crops, and potentially cashew trees for cacao farmers. The planting of trees that can be used for construction, such as teak, is more susceptible to illegal logging practices, as evidenced by the experiences of the farmers we interviewed. The Environmental Protection Agency reiterates that intercropping is the most beneficial method.

Given the evidence that intercropping represents the most effective method of agroforestry, it is clear that there is a need for farmers to be educated in these new practices. A framework must be established to exchange knowledge between farmers who intend to employ agroforestry techniques and to maintain trees correctly. Of all the agricultural knowledge that farmers must learn, pruning is the most crucial. Interviews with farmers and Ghana's governmental agencies revealed that farmers have acquired their current knowledge through observing the actions of another farmer in real life. Demonstrating the most effective methods is the optimal approach to ensuring farmers gain the requisite knowledge to maintain trees. To this end, a dedicated field must be selected on which a party demonstrates to farmers how an agroforestry plot is maintained over its lifetime. This approach can also demonstrate the system's benefits to the farmers, which may act as a catalyst for change.

The final concern that can potentially act as a deterrent for farmers who are considering adopting agroforestry practices is the current financial constraints they are facing. A review of the literature revealed that smallholder farmers currently lack the financial resources to make long-term investments, which represents a significant obstacle to the adoption of agroforestry practices. In the course of the interviews, the farmers themselves identified financial constraints as one of the most significant challenges they are currently facing. Furthermore, the farmers indicated that they lack the financial resources to procure both seeds and saplings, as well as the requisite tools for tree maintenance. It is, therefore, evident that another party must provide support to farmers to facilitate the transition to agroforestry. The Ghanaian government has previously implemented a project which distributed saplings to farmers. However, due to a lack of ongoing support following the distribution of the saplings, farmers were unable to maintain the trees. Consequently, the project was not deemed to be a success. Therefore, a party must assist farmers with both the financial aspect and by providing training to enable them to maintain the trees.

In addition to the Ghanaian government's provision of support, which may be motivated by an interest in Ashanti farmers' use of agroforestry methods, another option has emerged in recent years. The development of the carbon credit market has prompted numerous global entities to initiate forestry and agroforestry projects worldwide (Minoli et al., 2023; Nurrochmat et al., 2024). In these projects, a financial return can be obtained by cultivating trees, as trees can sequester carbon dioxide from the atmosphere. This additional financial incentive can serve as an extra motivation for farmers to transition to agroforestry practices. Furthermore, it could motivate third parties to make initial investments, as the carbon credit returns can serve as a business model for these entities. This would ensure their assistance with initial investments in seeds and saplings, as well as facilitate the exchange of knowledge regarding agroforestry methods among participating farmers. This option requires future research from the same comprehensive system perspective we used in our study to address the institutional, technical and social aspects of a carbon credit market. We reflect on this in the conclusion section.

Discussion

Feasibility of agroforestry in Ghana's Ashanti region

Despite the potential benefits that can be derived from implementing agroforestry methods, such practices remain uncommon in Ghana's Ashanti region. There are several principal reasons why this has not yet been implemented.

A review of the literature on the general context revealed that farmers are experiencing difficulties in making long-term investments due to the limited security of their land tenure. The farmers who participated in the study explained that they lack documentation regarding lease and land ownership. They also stated that their short lease terms of 1 year do not allow them to make investments for future years. Furthermore, the farmers indicated that they are not in a position to engage in conflict with local landowners and that there are no apparent conflict resolution mechanisms.

Additionally, farmers encounter constraints in their knowledge of agroforestry and in accessing financial resources. The current farming practices are based on traditional methods handed down through generations. The strong farming culture, which is closely tied to crop selection and local food traditions, presents a significant challenge for farmers when attempting to adopt agroforestry practices that involve different methods and new tree or plant species. Despite their interest in learning new agricultural techniques, farmers' lack of formal education makes them reluctant to adopt intercropping trees. Experiences have demonstrated that when trees overgrow their fields, it can have a negative impact on regular crops. This highlights the need for targeted training and capacity-building initiatives, particularly in teaching farmers proper thinning, trimming, and pruning techniques to ensure effective tree management without compromising crop yields. Furthermore, farmers often lack the financial resources to purchase and maintain saplings, as well as to acquire the tools needed for the upkeep and pruning of agroforestry trees. This highlights the necessity for initiatives that provide financial support to assist farmers in covering these essential costs when transitioning to agroforestry practices.

Conclusion

In our study, we adopted a complex systems perspective in which we analysed the institutional, social, and technical challenges that need to be overcome for a transition to sustainable agroforestry ecosystems. In their agroforestry experimental pilot study in Argentina, Comolli et al. (2024) show that such ecosystems enhance resilience to extreme weather events better than monocultures. Their pilot demonstrates that an agroforestry system can lead to moderate temperatures in the system, the retention of moisture as well as to fewer detrimental insects, leading to an increase in biodiversity (pp. 10–11). Our complex system perspective extends such pilot studies by looking at the local context in which the transition needs to be actualized by the local farmers. Our comprehensive analysis enables us to translate the challenges into the following recommendations for implementing an agroforestry ecosystem in Ghana.

First, farmers in Ghana's Ashanti region are unlikely to initiate bottom-up initiatives to transition to agroforestry practices; they need support to navigate the institutional challenges they face. The land tenure system appears to be the most significant challenge. Hence, we deem an increase in tenure security for farmers in Ghana a top priority. To this end, cooperation between smallholder farmers, the chiefs/landowners, relevant NGOs, or a third party as an intermediary stakeholder, and the Ministry of Food and Agriculture needs to be established. This reflects Elinor Ostrom's concept of polycentric coordination for common goals "to arrive at collaborative solutions that best fit the needs and properties of their action arenas" (Desrochers and Szumak, 2020, p. 145) rather than "a reliance on solutions imposed coercively from above" (ibid, p. 146). For this institutional redesign, a process design is needed to involve all relevant actors and to address the informal institutional environment (such as the local culture, norms and values; Koppenjan and Groenewegen, 2005).

Second, our study shows that capacity-building initiatives and training for growing and maintaining trees in an intercrop setting, as well as financial assistance, are required during the initial stages of adopting agroforestry practices. In interviews, farmers indicated that while the government attempted to provide saplings, these efforts yielded limited success because other identified issues were not adequately addressed. Although pilot studies such as those reported by, amongst others, Comolli et al. (2024) take an extended period of time, they can be used to demonstrate the advantages and the selection of a most suited agroforestry ecosystem for the local context. Such a pilot may also convince smallholder farmers and chiefs of the feasibility of agroforestry. And it can be used for training the required skills.

Third, given the required financial support in the start-up phase, we recommend the exploration of the potential benefits of utilising the carbon credit market. The distribution of carbon credit funds can serve as an incentive for farmers to participate by generating an additional revenue stream. The underlying principle is that agroforestry contributes to carbon storage and thus yields carbon credits, which can be bought by companies that want to compensate for their carbon emissions in their production process (Anjos et al., 2022; Kreibich and Hermwille, 2021). This can assist the above-mentioned third party in covering the costs associated with addressing the institutional, social, and technical challenges faced by the farmers. Furthermore, this approach can provide a viable business plan for the third party, enabling them to generate revenues while supporting farmers in their transition to agroforestry. Several efforts have been made to promote such practices in Ghana. For instance, the promotion of agroforestry practices as carbon sinks and a good base for income diversification is part of the REDD+ strategy developed by the United Nations Framework Convention on Climate Change (UNFCCC) in 2008 to foster climate mitigation (Ghana REDD Strategy, 2016). The 'Climate-Smart Agriculture Investment Plan for Ghana' by the Worldbank (2024) also considers agroforestry to be a promising climate mitigation technique as it has a positive impact on heat- and drought-tolerance, disease resistance, and soil fertility management.

Two examples of such projects are the ACORN initiative of the Dutch bank Rabobank, which is in the Kintampo, Techiman, Wenchi, Bole, and Sawla districts in Ghana in collaboration with the Ghanaian Ministry of Food and Agriculture (Rabobank, 2024). And in the fall of 2024, an agroforestry initiative was started near Kumasi; the 'Farm of the Future' (FoF) project, led by the organization reNature which aims to support 100 farmers with an additional revenue stream by utilizing carbon credits (ReNature, 2024).

Evaluations of projects to offset carbon emissions linked to agroforestry in Ghana have been conducted. For instance, Lee (2012) analyzed four agricultural carbon projects in the Northern and Western regions of Ghana that were led by the Rainforest Alliance, A Rocha Ghana, CARE International, and PARED and emphasized the potential for such carbon projects if those projects were able to effectively access the carbon market and address the high transaction costs involved and methodology issues that come with monitoring carbon. The Danish International Development Agency has funded an agroforestry project 'CLIMCOCOA', whose evaluation, among other things, concluded that context-specific socioeconomic and biophysical factors should be carefully taken into account to maximize the potential of agroforestry and avoid unintended social and environmental consequences. Another conclusion was that land and tree tenure need to be aligned with farmers' indigenous practices. They did not yet find sufficient clarity on key issues that come with the development of a fair and transparent benefit-sharing scheme that utilizes carbon credits in the promotion of agroforestry (Olwig et al., 2024).

Other potential revenues from agroforestry in Ghana have been explored as well. A study on agroforestry with farmers around Kakum National Park in the Central Region reveals an additional revenue income through sales of fuelwood made from the branches of the trees (Arhin et al., 2020). Another study on eight agroforestry farms in the Nandom Municipality in the Upper West Region of Ghana shows that farmers may have a specific preference for the tree type to be integrated with the crops. Some species are not conducive to crop productivity, whereas others are even giving multiple economic uses in terms of, e.g., food additive or medicinal value (Benebere et al., 2023). Furthermore, a study by Addo-Danso and Amankwaa-Yeboah (2022) explains how bamboo-based agroforestry systems can contribute more to crop productivity and improve soil fertility and pH levels when compared to monocropping systems. A comprehensive approach to assess the mix of potential sources required for financial support in the start-up phase of agroforestry by smallholder farmers in Ghana is needed.

Future research

Our study also contains limitations due to the choices in our research design. To address these limitations, we offer the following topics for future research.

First, this research was conducted with the invaluable assistance of smallholder farmers, governmental entities, and an NGO. Nevertheless, to more effectively address the current land tenure situation and the potential impact of agroforestry on the land tenure insecurity of farmers, the insights of chiefs within the Ashanti region are essential, as they are the primary stakeholders in the acquisition of land tenure agreements and related documentation. In addition, we selected the Ashanti region in Ghana based on its logistical suitability and the assumption that it could reflect broader regional trends. Still, other regions need to be analysed to assess and contribute to the generalisability of our findings.

Second, not addressed in our study is the role that indigenous knowledge can play in the transition to agroforestry, as explored by Ogunmekan et al. (2024), who study "the viability of a combination of the traditional beliefs and cultural ethos with ecological projects, in achieving … sustainable development goals" (Ogunmekan et al., 2024, p. 1). Such an analysis is an extension of the analysis of the social sub-system. It can provide deeper insights into the social fabric of small farmer communities that may be influenced by or influence the transition to an agroforestry ecosystem.

Third, a study into the complexities of the carbon credit market and the prevailing Ghanaian regulations on carbon market projects can be conducted. This study can assess whether utilising the carbon credit market to establish agroforestry projects is a viable option. The distribution of carbon credit monetary returns to fund the system needs to be included, e.g., to assess whether monetary returns from the carbon credit market can be employed to secure land agreements with traditional authorities. A more in-depth study into the contextual success factors of using the carbon credit market and additional revenues to stimulate the adoption of agroforestry is needed to assess the potential for large-scale implementations, also after the start-up phase.

Lastly, we recommend the study by Taillandier et al. (2023) entitled "Growing Resilient Futures: Agroforestry as a Pathway Towards Climate Resilient Development for Smallholder Farmers," which was published after the completion of our research project. Taillandier et al. used the Climate Resilient Development Pathway framework, focussing on creating concrete pathways to agroforestry adoption in the Global South. Their framework presents a tool for the establishment of agroforestry projects to provide support to smallholder farmers on a global scale.

Reflection on the position of a European researcher in a local context

The involvement of a European researcher in the Ghanaian context revealed a complex interplay of cultural differences. While Ghanaians expressed enthusiasm for engaging in the research, on occasion, interviewees provided responses that they believed to be aligned with the research objectives or answered without fully grasping the question. Subsequent discussions yielded different responses when farmers were afforded more time to consider the questions carefully. Furthermore, interviews with farmers were conducted with the assistance of a translator proficient in both local languages and English, as well as in agroforestry systems. Still, the necessity of translation introduced a layer of complexity, which may have influenced the empirical data.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by Human Research Ethics Committee (HREC), Delft University of Technology, the Netherlands. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

YD: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. JU: Conceptualization, Methodology, Supervision, Writing – review & editing. EA: Conceptualization, Methodology, Supervision, Writing – review & editing. LK: Conceptualization, Resources, Writing – review & editing.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Acknowledgments

We thank Farmerline in Ghana for supporting the research by facilitating the selection and access to the interviewees. We wish to thank all smallholder farmers in the Ashanti region in Ghana for their willingness to participate in this research, as well as the Ghanaian government officials from the Ministry of Food and Agriculture and Environmental Protection Agency for their input. Likewise, we thank Prosper Kugblenu, Ejura Agricultural College, for his insightful information on the local context. This article is based on research conducted in the context of a master thesis project at Delft University of Technology, the Netherlands.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 12 February 2025
DOI 10.3389/fsufs.2025.1380248

OPEN ACCESS

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RECEIVED 01 February 2024
ACCEPTED 03 January 2025
PUBLISHED 12 February 2025

CITATION
Manalo JA IV, Orcullo LGF and de Leon TJP (2025) Altruism as a scaling ingredient: an exploration of the adoption of the *Laboy tiller* in Aurora.
Front. Sustain. Food Syst. 9:1380248.
doi: 10.3389/fsufs.2025.1380248

Altruism as a scaling ingredient: an exploration of the adoption of the *Laboy tiller* in Aurora

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The *Laboy tiller* was developed to address the challenges of preparing fields with *laboy* soil conditions. This study uses the scaling ingredients framework developed by PPPlab and CIMMYT to examine how the machine scaled from its initial project in San Luis, Aurora, Philippines. In-depth interviews with farmers (n = 28) and key informants (n = 12) were conducted to address the research questions. The results show a lack of concerted efforts in addressing some of the scaling ingredients, such as collaboration, evidence and learning, leadership and management, and public sector governance. Consequently, the *Laboy* tiller experienced limited scaling outside of San Luis town. However, it had a profound impact on the farmers of laboy areas in Aurora, where the concept of altruism emerged as a critical scaling ingredient. Altruism facilitated the *Laboy* tiller's dissemination through the personal networks of its initial owners, who valued and maintained the machine over time. Recognizing altruism as a key scaling ingredient could enhance the scaling efforts of other innovations by encouraging beneficiaries to actively participate in the continued uptake and sustainability of introduced innovation.

KEYWORDS

altruism, technology adoption, technology adaptation, *Laboy tiller*, farm machine

1 Introduction

Rice cultivation is deeply woven into the Filipino social fabric (Manalo et al., 2020). The country has millions of rice farmers, and rice is celebrated as its favored staple. The Philippines is home to diverse rice-growing conditions. It has both favorable and unfavorable environments. Favorable environments are irrigated areas with an ample supply of water and those that meet the photosynthetic requirement for rice. These are also the areas that generate the highest yields in the country. Unfavorable environments prove challenging in growing rice, such as rain-fed areas or those that depend on the onset of rain before farmers can cultivate rice. *Laboy fields* are among the unfavorable environments for rice growing. *Laboy* fields are characterized by soft, low-bulk-density soil with deep mud reaching the waist (Regalado and Juliano, 2010). These fields were formed from the clearing of former swampy forests by the Philippine government's Agrarian Reform Program; hence, they were also referred to as basal by the locals of Aurora. Due to the waterlogged conditions, there is a buildup of organic matter at various stages of decomposition. This bulk of organic matter, peat soil, has a low density and floats in water. An area in San Luis, Aurora, was named *'yanig'* (tremor) because of the way the *laboy* soil shakes as one steps on it. As there is a layer of peat floating on water, land preparation was done by manually cutting blocks of this layer and then turning it over to submerge the growing weeds. Traversing the field is difficult as the mud acts like quicksand; hence, the locals kneel to increase surface area as they move through the field.

The *laboy* soil stores carbon efficiently, where organic matter content is 70% or higher, whereas 5% is already considered high. Because of this high organic matter content, there are deficiencies, such as zinc deficiency and toxicities in the soil. Furthermore, because of the decomposition of the organic matter, the soil is also acidic (Sandro Cañete,[1] face-to-face conversation with author, June 8, 2022). *Laboy* fields are among the most challenging conditions in rice cultivation in the Philippines. On average, rice yield in *laboy* fields is only approximately 2 t/ha due to the difficulties in land preparation (Regalado and Juliano, 2010). In the early 2000s, there were approximately 15,000 ha of *laboy* rice fields across the country, with more than 1,000 ha in Aurora alone. Other provinces in the Philippines with *laboy* conditions include Cagayan, Pampanga, Oriental Mindoro, Samar, Surigao, Agusan del Sur, and North Cotabato (Regalado and Juliano, 2010). To address issues in *laboy* fields, the Rice Engineering and Mechanization Division (REMD) of the Philippine Rice Research Institute (PhilRice) developed the *Laboy tiller* in 2003. *Sitio Hiwalayan* in San Luis, Aurora, was the site for a demonstration of the PalayCheck System, where the PhilRice crew encountered the difficulties of the farmers with their *laboy* fields. The PalayCheck System is an integrated crop management platform for rice to assist farmers in achieving desired yield increases. Land preparation was performed manually, as heavy machinery would sink in the mud. The land is prepared by cutting the floating soil into blocks and turning them over by hand to bury the weeds. Different types of machinery, such as the Turtle Tiller or the '*Pagong*,' as well as the hydrotiller from the International Rice Research Institute (IRRI), were introduced earlier in the area to address issues in *laboy* fields. However, they were unsuccessful as the farmers observed the machines having frequent bog downs (Regalado et al., 2007).

Participatory development followed for the *Laboy tiller* with REMD through the initiative of Dr. Manuel Jose Regalado, a PhilRice scientist under the REMD and part of the crew in the demonstration of the PalayCheck System mentioned earlier. Some of the farmers tested the prototypes and recorded their observations. Data on the machine performance and farmer's insights were collected in developing the Laboy tiller. The initial target was a riding-type tiller to address the difficulty of traversing the *laboy* fields—described by farmers as kneel-walking on land without a hard pan. However, after feedback from the farmers who had tried the prototypes, the riding type was scrapped as they preferred lower fuel consumption and found the machine difficult to maneuver when seated.

This study explores the factors that affected the technology uptake of the *Laboy tiller* almost two decades after its development. Insights from this study could serve as inputs in developing technologies by agricultural research institutions across the globe. The next section of this study presents the literature review covering information and insights on *laboy* soil, the level of mechanization in the Philippines relative to other rice-producing countries, and factors affecting technology uptake. The theoretical framework, specifically the 10 scaling ingredients, is presented.

2 Literature review

2.1 Mechanization

Mechanizing rice cultivation is central to the agenda of the Philippine government to make the sector more competitive. The cost reduction from the mechanization of labor-intensive tasks, such as land preparation, crop establishment, and harvesting, has a significant impact on raising the competitiveness of locally produced rice, with labor costs amounting to 37% of the total production cost in Nueva Ecija (Bordey et al., 2016). Compared with the mechanization level of other Asian countries with data from 2011, the Philippines (1.23 hp/ha for all crops; 2.31 hp/ha for rice and corn) is way behind countries like Japan with 18.87 horsepower/hectare (hp/ha), Korea with 9.38 hp/ha, China with 8.42 hp/ha, and Thailand with 4.20 hp/ha (Bautista et al., 2017). Furthermore, in a study validating the modified agricultural mechanization index for lowland rice ($MAMI_{rice}$), Amongo et al. (2018) found that the computed $MAMI_{rice}$ for the three provinces in their study was way below the ideal theoretical computation of 5.071 hp/ha needed to achieve 6 tons of yield per ha. The computed $MAMI_{rice}$ in the man–machine system in the three provinces in Amongo et al.'s (2018) study using rototilling and combined harvesting operations are only 1.780 hp/ha for Oriental Mindoro, 1.232 hp/ha for Laguna, and 2.505 hp/ha for Quezon.

Bautista et al. (2017) noted that small and irregular landholdings that could be inaccessible during the rainy season are among the key challenges in achieving full farm mechanization in the Philippines. In comparison, countries like Korea and Japan have had some success in consolidating their farmlands, enabling greater mechanization (Bautista et al., 2017; OECD, 2009). Another issue discussed by Bautista et al. (2017) is the high price of machines coupled with the low buying power of farmers that could be circumvented through custom hiring services to give marginal farmers access (Kadhim, 2018; Rawat et al., 2020).

2.2 Adoption

Various studies have been conducted to determine factors affecting agricultural innovation adoption (Connor et al., 2021; Cafer and Rikoon, 2018; Glover et al., 2017; Mottaleb et al., 2016; Obeng Adomaa et al., 2022; Orr, 2018). Orr (2018) finds the importance of market demand and overcoming production and seed delivery constraints for the adoption of improved seeds. Connor et al. (2021) find in their study on sustainable rice that ease of implementation and non-rice income are the main drivers in adopting individual requirements. In a study on small-scale agricultural machinery adoption, Mottaleb et al. (2016) find household assets, credit availability, electrification, and road density as factors that are positively associated with machine ownership. Cafer and Rikoon (2018) also find that cash and capital influence the decision to adopt more than contact with the agricultural innovation system, which shows the importance of addressing resource constraints to enable adoption. The variability and context of the location should also be considered when looking into the factors affecting adoption. Glover et al. (2017, pp. 17–18) discussed the concepts of 'inscription' and 'affordance,' indicating how innovations could be adapted by the users despite the 'inscribed' uses, as designed by developers, through the 'affordances' of the innovation or its potential uses. 'Inscription' pertains to how the designers and engineers set how innovation is to be used in contrast with 'affordances,' which entails the innovation's potential uses even if it goes against the designer's intended use (Glover et al., 2017, pp. 17–18). Obeng Adomaa et al. (2022) used these concepts in their study, tracing the pruning practices from research to farms in Ghana's cocoa sector. They find the importance of unpacking the affordances to better fit the local context, as this will make the process more meaningful for the farmers than the standardized recommendations developed from research (Obeng Adomaa et al., 2022). These concepts shift the focus from how an innovation is adopted to how it could be or is being adapted by the end users to better fit their needs. With respect to the existing literature, this current study contributes by using the 10 scaling ingredients to see how adoption or adaptation takes place in the context of the *Laboy tiller*. As will be elaborated in the next section, the scaling ingredients provide a better lens and tighter grip on factors that surround the adoption or adaptation of the technology in question.

2.3 Framework

With the aim of the study to explore the factors affecting the technology uptake of the *Laboy tiller*, we were guided by the concepts of German et al. (2006) that propose "a methodology for tracking the 'fate' of technological interventions in agriculture." German et al. (2006) shift away from the paradigm of technology transfer that sees innovation as something static passed on from researcher to the farmers through extension and aims to gain insight into the spontaneous spread and adoption of technologies, recognizing the importance of the continued reinvention of these technologies to better adapt them to the needs of the end-users. The study follows German et al.'s (2006, pp. 2–3) guide questions looking at the uptake of technology:

- "What are the pros and cons of each technology and the primary barriers to more widespread adoption?
- What were the social and farming systems' "uptake niches" of different technologies?
- What innovations and adaptations were made to the introduced technologies and why?
- Did introduced or modified technologies have any positive or negative impacts on livelihood?
- Did introduced or modified technologies have any impact on agroecosystem resilience?"

These questions explore how the technology was assessed by its recipients as they exercised their agency to decide if the technology was compatible with them. The findings were then incorporated into the 10 scaling ingredients from Jacobs et al.'s (2018) scaling scan tool as we assessed the technology's capacity to scale wider. The scaling ingredients, as introduced by Jacobs et al. (2018, pp. 10–14), are:

- Technology/Practice: Asks if the innovation has a relative advantage over other solutions to the issues that the innovation aims to solve
- Awareness and Demand: Ask if the innovation is seen as necessary or desirable and if they have access to information regarding this innovation
- Business Cases: Ask if the business for the innovation is viable across all actors in its value chain
- Value Chain: Asks if the links between the actors are effective in pursuance of their business case
- Finance: Asks if effective financing options are available for users and value chain actors
- Knowledge and Skills: Asks if the intended users can use the innovation
- Collaboration: Asks if relevant actors to the innovation are sufficiently engaged
- Evidence and learning: Ask if evidence is being gathered for the understanding of the scaling of the innovation
- Leadership and Management: Ask if effective coordination toward scaling is followed by relevant actors
- Public Sector Governance: Asks if the government is supportive of the scaling ambition

The study by Manalo IV et al. (2022) may be consulted for a comprehensive discussion of the scaling ingredients.

We also draw from the Unified Theory and Acceptance and Use of Technology (UTAUT) to sharpen our analysis. This theory unifies several established theories from various disciplines to develop a more holistic understanding of technology acceptance and use. The main premise of this theory is that the use and acceptance of technology are guided by behavioral intention. Along this line, there are four key considerations: performance expectancy, effort expectancy, social influence, and facilitating conditions. Performance expectancy pertains to how good a technology is at addressing the key concerns of the user. That is, if a technology is fit for purpose. Effort expectancy is the degree of ease in using the technology, i.e., it should not be too difficult to use. Social influence refers to the perception of the individual that "important others believe that s/he should use the new [technology]." Lastly, facilitating conditions refer to the belief of an individual that there is a supportive organization and technical infrastructure in using the new technology (Venkatesh et al., 2003).

Figure 1 combines the key insights from German et al. (2006), Jacobs et al. (2018), and Venkatesh et al. (2003). Of these three references, the work of Jacobs et al. (2018) provides a good rallying point for the concepts used in this study. For example, question 1 of German et al. (2006) on the pros and cons of the technology and its barriers are captured in the "Technology/practice" scaling ingredient. The same can be said of the impact on livelihood. The other questions are easily subsumed under the different scaling ingredients. The four key elements in the work of Venkatesh et al. (2003) also fall under the 10 scaling ingredients. For example, "facilitating conditions" relate to "leadership and management" and "public sector governance." "Social influence" in the work of Venkatesh et al. (2003) relates to "altruism" and "awareness and demand." While Jacobs et al. (2018) provide an all-encompassing theory, we argue that the other two references enhance the explanatory power of the overall theory, which then contributes to sharpening the analysis in this study.

3 Methodology

The main site of our inquiry was Sitio Hiwalayan, Barangay (village) Bacong, San Luis, in the province of Aurora, where the development of the *Laboy tiller* started. Then, nearby areas with *laboy* soil located in Reserva and Calabuanan in the town of Baler and Mucdol and Maligaya in Dipaculao town were also covered based on the recommendations of farmers from earlier interviews. The municipalities of San Luis, Baler, and Dipaculao are connected, with Bacong and Calabuanan situated adjacent to each other and Reserva, Mucdol, and Maligaya also clustered together.

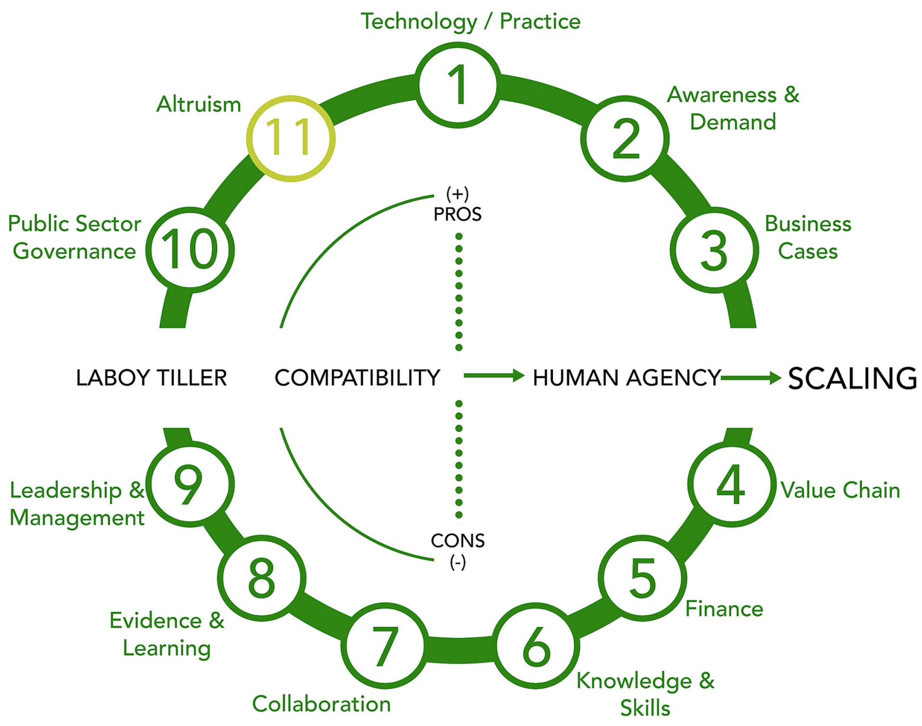

FIGURE 1
Framework of the study.

We conducted in-depth interviews with 28 farmers for this study through face-to-face, semi-structured interviews designed to be flexible with respect to the information and narratives the respondents were willing to share. The first farmer-interviewees were referred to us by Dr. Manuel Jose Regalado, or "Doc Manny," as the technology developer, and were traced with the help of the officials of the relevant Office of the Municipal Agriculturist (OMAg). The succeeding farmers were either referred to us by officials of the OMAg in San Luis, Aurora, or by the farmers that we had earlier interviewed. This process of selecting samples is called snowball sampling. Further referrals were traced from the suggestion of the succeeding farmers until the suggestions were pointing back to farmers that had been interviewed, and the succeeding interviews returned similar key points suggesting theoretical saturation. Aside from the farmer participants, we also had 12 non-farmer stakeholders that we interviewed to gain vital context about the innovation and the research sites. We interviewed staff members from the local government units (LGUs) ($n = 6$) that serve the areas where our research sites are located. We also interviewed mechanics ($n = 2$) referred to us by the farmers we interviewed who avail themselves of services for the maintenance and upkeep of their machines. PhilRice staff members ($n = 3$) who were involved with the development of the machine were also interviewed, as well as a manufacturer (1), referred by the PhilRice staff members, who are licensed to manufacture the machine. In our analysis, we transcribed all interview recordings, and they were read line by line by the three authors during the coding process. We also had a code guide to ensure reliability and consistency as each author coded the transcripts. The authors compiled the emerging codes in the coding process and deliberated through meetings to decide the final codes that would be used in the code guide. We did informal member checks to enhance the soundness and authenticity of our analysis (Lincoln and Guba, 1985). We also did a formal member-checking session where we presented our findings to the farmers to reduce, if not diminish, errors in the representation of their lived experiences with respect to the *Laboy tiller*. We alternated inductive and deductive analysis to make sense of our findings. All research participants were anonymized in this study.

4 Results

4.1 Scaling ambition

Adopting Jacobs et al.'s (2018) scaling scan tool to formulate the scaling ambition of the *Laboy tiller* in our research site for the area, we conceptualized a continuum (Figure 2). As there were multiple actors during the period covered by this study, we determined that different scaling ambitions were made at different points in time by different actors. Illustrated in Figure 2 are some of the important points we found in this continuum.

Using the tool by Jacobs et al. (2018), we were able to (re)construct the initial scaling ambition as follows:

> *By the end of the participatory development on the Laboy tiller, the PhilRice Rice Engineering and Mechanization Division (REMD) wants to see increased uptake of the Laboy tiller stemming from their earlier work in Sitio Hiwalayan. The overarching goal was to do away with manual land turning and hence make their land preparation labor easier and more efficient.*

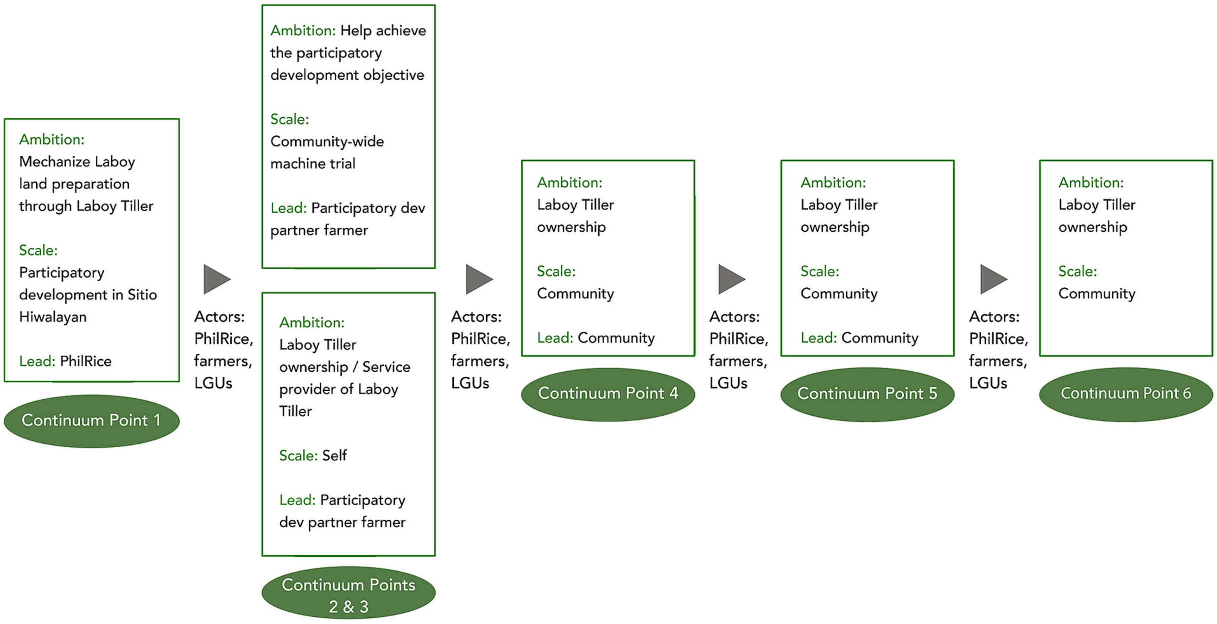

FIGURE 2
Continuum points in the study.

Continuum points 1–3 refer to the conceptualization of the *Laboy tiller* until it has reached some level of acceptability on the part of the farmers in the study sites. At this juncture, the *Laboy tiller* has become known in the community, and there is demand for more *Laboy tiller* units (continuum point 4), opening up for the remaining ingredients on the supply chain, financial cases, knowledge and skills, and collaboration (continuum point 5). After the second wave of unit provision and training, PhilRice REMD's engagement with the community regarding the *Laboy tiller* was also terminated. The remaining ingredients of evidence and learning, leadership and management, and public sector governance become more discernible once the community is left on its own (continuum point 6).

4.2 Scaling ingredients

Jacobs et al.'s (2018) scaling scan tool proposes 10 different ingredients representing fields that need attention for the success of the scaling ambition. In the following paragraphs, the state of each scaling ingredient concerning the uptake of the Laboy tiller is discussed. Key points regarding each ingredient are summarized in Table 1.

4.2.1 Technology/practice and knowledge and skills

The practice when the *Laboy tiller* was being developed was manual land turning. As reflected in our interviews, this practice is tedious and may also be ineffective. The weeds are still rooted in the soil; some may still grow back. This gives the *Laboy tiller* a high relative advantage.

> *"The technology they practice is manual. They just turned over the weeds before. When weeds grow when no crop is planted, they turn it over manually. Alas, the weeds are surely still alive since they just turned it over.[2]"*
>
> *[LGU official from Bacong]*

Other comparable technologies are floating tillers, such as the Turtle Power Tiller and the IRRI Hydrotiller. However, they had often bogged down; hence, these floating tillers did not gain a following in the area. In comparison, the *Laboy tiller* reliably floats (Figure 3). Furthermore, regarding the Turtle Power Tiller, the interviewees shared that among their difficulties with it is that it has little traction to go forward once the weeds have been mulched up. It works fine on the first passing as it gains traction from the weeds, but the operator will have to expend much effort to push it through for a second passing. In comparison, the *Laboy tiller* has cross paddles attached to the cage wheel to facilitate forward movement (Figure 4). This feature is among the results of the participatory development activity.

> *"It [Turtle Tiller] won't move forward because it can't find traction, it wants to always have something to grab on. Unlike the floater [Laboy tiller], even without anything to grab on, it will run.[3]"*
>
> *[Farmer from Bacong, M, 60]*

The Hand Tractor has become popular in recent years due to the changing landscape of the area. This shift can be attributed to the canalet-digging initiative undertaken by farmers with support from local government units. By digging canalets around their fields to drain water, the *laboy* fields gradually solidified over time, leaving only a few deep areas. This transformation paved the way for the increased use of Hand Tractors. On shallow land, Hand Tractors operate much faster than the *Laboy* tiller, making them the preferred option when deep areas are minimal. Additionally, innovations have

TABLE 1 The scaling ingredients with respect to *Laboy tiller* uptake.

Scaling ingredient	Key points
Technology/practice	• The *Laboy tiller* is a huge improvement over the manual land-turning • The Hand Tractor is preferred over the *Laboy tiller* as long as the mud is not too deep, as it works much faster • Other floating tillers tested in the area, like the Turtle Power Tiller and the IRRI Hydrotiller, were not successful
Awareness and demand	• The use of the *Laboy tiller* spread through the personal networks of the initial owners of the machine, mostly through custom hiring services • It did not spread much outside of the personal networks of the owners, with respondents we interviewed from farther areas having no awareness of the machine
Business cases	• The *Laboy tiller*, being more complex than the Turtle Power Tiller, is more expensive to manufactures and with its highly niched demand, the manufacturer does not get too many orders for this machine outside of government-initiated procurements • Service providers gained profits
Supply chain	• Basic maintenance of the *Laboy tiller* can usually be managed by the user • There are also repair shops nearby for repairs that could not be managed by the user • There are parts that are not available in the area and would have to be sourced from Nueva Ecija
Finance	• The soft loan program from the Rice Engineering and Mechanization Division of PhilRice was what enabled most of the users to purchase their units
Knowledge and skills	• The *Laboy tiller* is fairly simple to operate
Collaboration	• After the initial project, there was no set collaboration of key actors for the scaling of the *Laboy tiller*
Evidence and learning	• There is a lack of further monitoring after the initial project was completed
Leadership and management	• After the initial project, there was no leader set to manage closely the scaling of the *Laboy tiller*
Public sector governance	• The scaling of the *Laboy tiller* does not seem a priority for the public sector

FIGURE 3
Photo of the *Laboy tiller*.

been introduced to enable Hand Tractors to navigate deep areas. One such innovation involves bridging the tractor over these areas using bamboo. Another strategy employs cage wheels, which are wide enough to remain unaffected by sudden dips in the field. To further enhance their efficiency, the sides of the cage wheels can be covered to prevent soft mud from entering and obstructing the Hand Tractor.

In terms of speed, the Hand Tractor is much faster. One of our interviewees advances that the *Laboy tiller* can prepare the land better as the spikes of its cage wheels ensure that the weeds are cut up. In contrast, the Hand Tractor with cage wheels cannot have spikes, as the engine may be unable to handle the added load due to the added resistance. Furthermore, they usually modify it to be wider to still find footing with narrower deep areas, which adds significant load to the

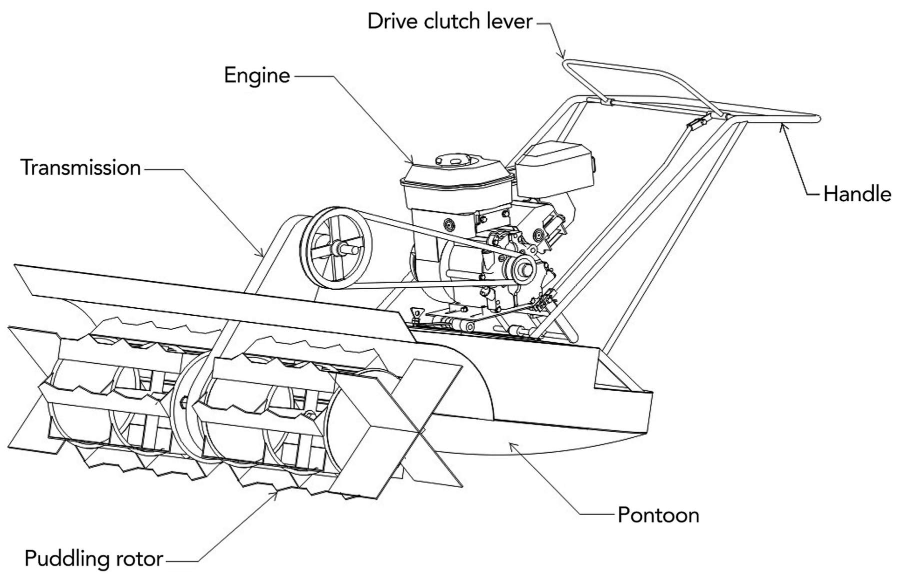

FIGURE 4
Diagram of *Laboy tiller* with the cross paddles incorporated into the puddling rotor. Reproduced from Regalado and Juliano (2010); with permission from PhilRice.

engine. Also, a stronger and heavier engine cannot be used as the Hand Tractor may just sink if it becomes too heavy.

> *"Interviewer: What is this spike? Is it better if it has spikes, or like…*
>
> *Interviewee: That is what's nice*
>
> *Interviewer: It could really crush the…*
>
> *Interviewee: Yes, it could really crush the stalks and weeds. Because what we use before doesn't have [spikes], it just topples the stalks and weeds*[4]*"*
>
> *[Excerpt of Interview of Farmer from Mucdol, M, 58]*
>
> *"Interviewee: It is also hard. The engine will be overburdened because it is big.*
>
> *Interviewer: If it is bigger, the engine becomes overburdened? Why so?*
>
> *Interviewee: You also can't put a bigger engine as you'll be heavier*[5]*"*
>
> *[Excerpt of interview with a farmer from Mucdol, M, 58]*

Recognizing the pros and cons of the two machines, some farmers innovated by combining them. During one of our visits, we witnessed a land preparation activity where the farmers alternated *Laboy tiller* and Hand Tractor on the same field so that the two machines complemented each other.

> *"Yes, it is still being used because if you know that it's deep, [SIC] you shouldn't use the Hand Tractor over it. Instead, go around it and finish it with the Floating Tiller*[6]*"*
>
> *[Farmer from Bacong, M, 60]*

Furthermore, the machine is easy enough to use and operates similarly to a Hand Tractor. According to one of the farmers we interviewed, if you know how to use the Hand Tractor, then you already know how to use the Laboy tiller.

> *"If you already know how to use the Hand Tractor, you already know how to use it, too*[7]*"*
>
> *[Farmer from Bacong, M, 60]*

4.2.2 Awareness and demand

The term '*Laboy tiller*' did not gain popularity among the farmers, resulting in some confusion. In our interviews, the *Laboy tiller* was referred to by the general term 'Floating Tiller' and sometimes also called *'Pagong'* or 'Turtle Tiller,' which confuses it with the actual Turtle Power Tiller, especially with those who only had experience with the machine through service providers, those who own the machine that is hired to work on the fields of others. The negative experiences of others with the Turtle Power Tiller, such as its often being bogged down, are also attached to the *Laboy tiller*, as some thought that it was the same as the Turtle Power Tiller. During the interviews, we utilized a printout of the pictures of the different machines to ensure accuracy. Nevertheless, regardless of the term, it is still quite easy in Bacong to find a service provider for *laboy* fields because of the personal network of the people there. It is a place where everybody knows everybody. However, farmers from areas farther from Bacong, such as in Dipaculao, are unaware of the machine.

The changing situation of their farmlands decreases the demand for the *Laboy tiller*. With their fields drained, more can be prepared faster with the Hand Tractor. The issue comes in the areas where the canalets are ineffective, such as in low areas where the canalets cannot drain the water. Furthermore, if there is a huge amount of rainfall, their canalets may be overburdened, essentially turning back their fields into *laboy*. This is further exacerbated in areas with infrastructure development, such as highways, which trap the drained water and the rainwater. The service provider that we interviewed also said that sometimes he has to turn down requests as he is already fully booked, indicating that there is demand for the *Laboy tiller* that has not been fully met.

> *"Interviewee: Ma'am, if the rainy season is too… it easily gets flooded and the soil floats*
>
> *Interviewer: During [SIC] rainy season*
>
> *Interviewee: Yes, also in the sunny season, whenever it rains too much, it floats, like organic soil that floats because it is light[8]"*
>
> *[Excerpt of Interview with Farmer from Bacong, M, 63]*
>
> *"When the road was developed, the laboy areas further increased[9]"*
>
> *[Farmer from Mucdol, M, 58]*

4.2.3 Business cases and finance

The more complex design of the *Laboy tiller*, compared with the Turtle Power Tiller, means that it would also cost more to manufacture. According to a manufacturer interviewed, the Turtle Power Tiller is preferred because it is simpler to manufacture. Furthermore, because of the COVID-19 pandemic, he also notes that it is much harder for farmers to build capital to invest in more expensive machines. Moreover, the fact that *Laboy tiller* serves a niche demand does not help build the business case of the manufacturer.

With limited demand from private farmers, most of the *Laboy tiller* orders were drawn from government procurement efforts. However, a business case based on government procurements may be difficult for small manufacturers, given highly bureaucratic processes. Smaller manufacturers who mainly sell a small number of units per order cannot participate in bigger procurement biddings even if they have the capacity for it. Furthermore, payment of government orders, in general, often takes too long to complete, necessitating bigger capital funds to continue functioning the business while waiting for the payment from a big order that costs a huge amount of money to manufacture. In addition, manufacturers pay some fees to renew their accreditation.

In terms of financing, the soft loan program of the REMD enabled some farmers to avail themselves of their units since December 2006. However, after REMD's involvement in the area, there were no longer any financing programs to help the farmers procure the machines. The last recorded purchase through the soft loan program was in June 2010.

There is a more promising business case on the side of the service providers. As we discussed earlier, the service provider we interviewed had to turn down some requests. Thus, more service providers can establish their business in the area. Furthermore, another farmer we interviewed who was also a service provider shared that he only gave up being a service provider because of his old age.

The farmers rely on their social network to avail themselves of the services of people who own a *Laboy tiller*. The promotion of the *Laboy tiller* also heavily depended on these personal connections. Personal connections have been vital, from the developers establishing rapport with farmers in their participatory approach to the farmers relaying their contacts through their social network. The farmers also passed on their units through their connections. However, as the promotion of the *Laboy tiller* mostly depended on these personal connections, the unit's usage did not spread widely. In Calabuanan, a neighboring village of Bacong, there remain people who have contacts with service providers of the unit from San Luis. However, in other research sites, such as Reserva, Mucdol, and Maligaya, we did not find anyone familiar with the *Laboy tiller*. For context, these are just surrounding villages, as shown in Figure 5.

4.2.4 Supply chain

It is difficult to purchase a unit from Aurora, as the nearest manufacturer will come from Nueva Ecija, approximately 80 km away. For context, the road network connecting Nueva Ecija and Aurora has only recently been paved. However, for the post-purchase servicing, the farmers could usually handle the basic repair and maintenance of the machine as they also have some tools for it. There are also auto repair shops where they bring the unit if they cannot handle the needed repairs. Even so, some specific parts may be unavailable and could only be sourced generally from manufacturers like the one in Nueva Ecija. They also have some modifications done on their units, such as on the handle to make it longer and on the engine bracket to fit different engines.

4.2.5 Collaboration, evidence and learning, leadership and management, and public sector governance

There was a strong sense of collaboration between the engineers who developed the machine and the farmers who participated in the development of the *Laboy tiller*. During the creation of the *Laboy tiller*, the farmer-cooperators diligently documented their experiences and evaluated the prototypes, as agreed with the developers, before involving them in the trials. However, collaboration between key actors diminished after the initial project, and regular monitoring was infrequent.

After the project, no key leadership or management was set up to focus on the scaling of the machine. The machine was promoted and procured for farmers through other PhilRice projects, which proved useful. However, there was no concerted effort to sustainably establish it in new areas. Furthermore, the LGU mostly works through procurement of what is needed as farmers requested in terms of machinery aid, where the scaling out and active promotion of units is not the priority. Given that farther areas are unaware of this technology, it would be logical to think that this machine would also not be requested.

4.2.6 New scaling ingredient

Scrutinizing the findings above, it becomes apparent that with all the imperfections of the machines and the innovation ecology, *Laboy tiller* seems to have withstood the test of time. While it did not go very far in terms of scaling, it also did not die down. In the words of a farmer-adopter, it remains the best machine in their town in dealing with *laboy* soils, i.e., after 19 years since it was introduced in San Luis,

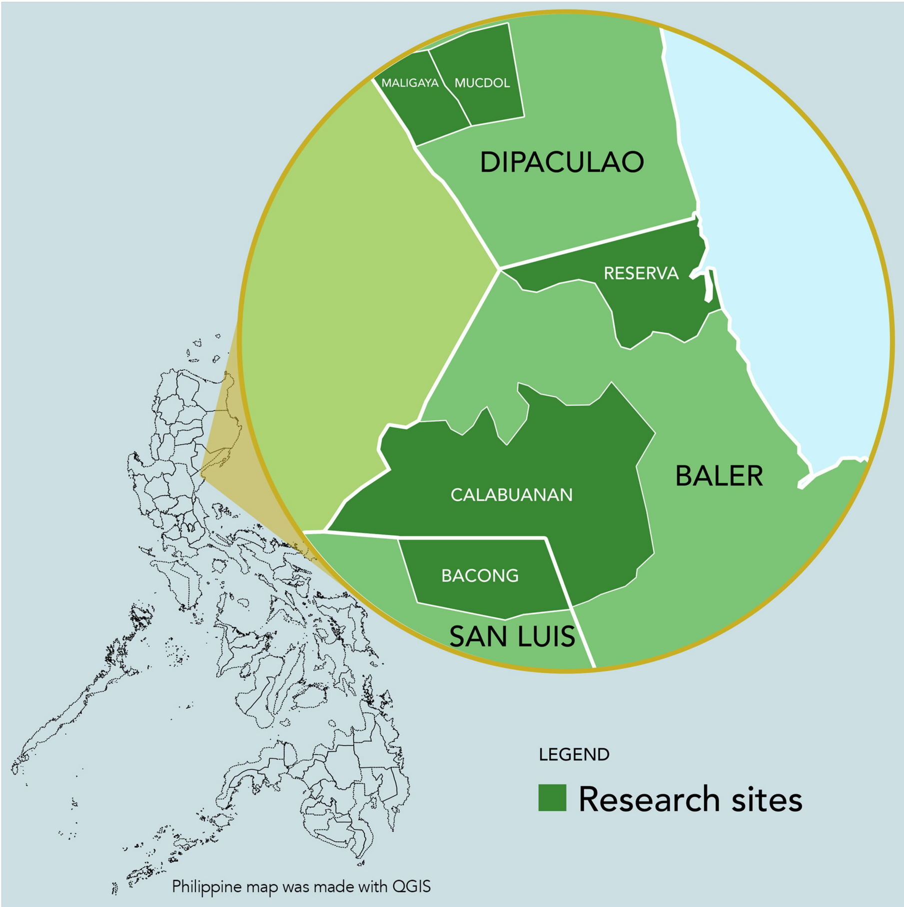

FIGURE 5
Map of the research sites.

Aurora. Many reasons could explain why this is the case. From our data, we argue for the role of 'altruism' in the technology uptake and the near-scaling process.

Broadly, altruism is defined and understood as the "disinterested and selfless concern for the well-being of others" (Bhuvana et al., 2021, p. 706). However, Kraut (2020) also expounds that acts could have a mixture of motives but remain altruistic, differentiating between mixed motives and 'pure' altruism. Returning to the scaling ambition described in Figure 1, we argue that altruism is interwoven in the process. Firstly, *Laboy tiller*'s development could very easily be considered an altruistic gesture (continuum point 1 in Figure 2), stemming from the desire to do something about the land preparation situation. For context, researchers can choose to tackle any research question or technology they wish to pursue, given the available resources, as long as it aligns with organizational priorities. Choosing to address the *"laboy"* issue was not imposed on the researchers but was a decision based on their judgment and capacity to address. It should also be mentioned that the original intent in going to Aurora was to do a demonstration for the PalayCheck, which is the Philippines' key platform to assist farmers in achieving decent yields. It was not meant to focus on the *Laboy tiller* or the *laboy* fields, which do not merit investment if seen from a business perspective. This shows that the act of choosing to work on the *'laboy'* issue could be read as an altruistic move.

As the participatory development rolled out, at the machine trialing phase, one farmer-partner was identified to steward it when the machine was left in the community, "model" it, and record observations. The scale of trialing expanded when this partner enjoined other farmers in the exercise (continuum point 2 in Figure 2). The first act of altruism had its first ripple effect here. Going back to the framework, the inclusion of the farmer as a co-developer aligns with 'performance expectancy.' Here, the REMD team of Dr. Regalado was trying to show that the technology can address a pressing issue.

By the end of the participatory development period, Doc Manny proposed to the farmer-partner that if he would like to buy the machine, he should be paid in tranches within the farmer's capacity to pay (*hulug-hulugan*). Had the farmer agreed to pay in tranches, Doc Manny would have to pay in case the farmer is unable to pay his dues. To highlight Doc Manny's gesture, it should be noted that *Laboy tiller* was not yet commercialized. The business aspect was not yet in the picture, as PhilRice is not into manufacturing. It is a purely research-for-development organization. Mass production is done by a private entity. Doc Manny was just after collecting some data to establish the machine's efficiency. This was the second altruistic gesture. It was favorable for the farmer partner, who had also realized the prospect of a servicing business (continuum point 3 in Figure 2).

During the interviews for this current study, the first farmer-cooperator speaks of his interaction with the research team as though it happened just recently, even after approximately two decades since he participated in the development of the *Laboy tiller* in 2003. In his narrative, the farmer would repeatedly mention the warmth and sincerity that he felt when the machine was being introduced to them – first as part of the participatory machine development addressing their *laboy* production concern and second as an arbitrary gesture of *kabutihang loob* (kindness) post-research. In Filipino culture, showing goodness to others is valued highly. Hence, we are inclined to think that the altruistic gestures may have resulted in the farmer valuing the machine developed specifically to address their main concern.

> *"What Doc Manny (Dr. Manuel Jose Regalado) has done for me is, he left the Floating Tiller, then he told me that I just need to record all that I do with it, how many passes, how much gasoline, that's what I report to him, but, no payment. He won't charge me for payment. Ergo, that's just what he says to me, 'How many days have I done', 'How many passes have I done', 'How much gasoline have I used', 'How many people were we'. Questions like that are what he asks me. So, in the end, he said that maybe if I wanted, I could pay in installments, and what happened was, the very first Floating Tiller that came here in Baler, Aurora, became mine.[10]"*
>
> *[Farmer from Bacong, M, 60]*
>
> *"I have no bad comments, only good ones! The Laboy tiller is very helpful!"[11]" [Farmer from Bacong, M, 60]*

Seen in this light, we argue that the Filipino value of *'utang na loob'* may have also played its part as a product of the altruistic gesture. *Utang na loob* is a key concept in Filipino culture that has been the subject of various studies (Agaton, 2017; Gundran et al., 2021; Kaut, 1961; Pe-Pua and Protacio-Marcelino, 2000; Rungduin et al., 2015). The academically dissected concept built upon (Kaut, 1961; Gundran et al., 2021) emphasizes *utang na loob* as a cycle of obligations and voluntary paying back to the donor. There are both positive and negative implications of this cycle of obligations, whereas one may take advantage of the system and offer a gift to someone to obligate them to give back something greater. On the other hand, it could also foster a strong relationship when, in the series of back and forth, both parties feel equally indebted to each other (Agaton, 2017; Kaut, 1961). Rungduin et al.'s (2015) study analyzed the *utang na loob* concept based on the meanings ascribed to it by their study participants, which helped them understand the contemporary meaning of the term. They synthesized three themes ascribed to the meaning of *'utang na loob'*: acknowledgment, reciprocity, and social responsibility. With altruistic acts (seen as *kagandahang-loob*) resulting in indebtedness and the need to pay back (*utang na loob*), we find that this social aspect can help in the farmers' willing adoption of presented technologies if the altruistic ideals are sincere and clearly shown. Sincerity, we argue, in this case, has to be felt by the recipient of the action. The developer's sincerity and purity of intent may have positively influenced the uptake and long-term use of the technology.

For this reason, we propose including altruism as among the scaling ingredients. Despite all the challenges, the *Laboy* tiller has remained and is regarded as an important machine in dealing with *laboy* fields. For a technology to scale, it has to first stay. In the case of this study, altruism is a key ingredient in why the *Laboy tiller* has since stayed. This proposal sits well with the calls relating to humanizing agricultural extension and considering social aspects often neglected in agricultural extension, usually dominated by discourses on technological determinism (Vanclay, 2004; Cook et al., 2021).

5 Discussion

The use of the *Laboy tiller* had spread throughout Bacong, mostly due to the service providers and the personal network of the people in the area. This parallels Stræte et al.'s (2022) discussion on the importance of networking as a social integration mechanism that strengthens a group's absorptive capacity. Through bonding and bridging social capital, the service providers can easily access their social groups and other nearby social groups (Cofré-Bravo et al., 2019). In the framework, this relates to "social influence" or the belief that important others believe that farmers should use the technology.

Group involvement through these social groups facilitates the spread of awareness regarding the relative advantages of this innovation (Kuehne et al., 2011). However, due to weak linkages with other social groups in surrounding areas, awareness is largely confined to Bacong. This limitation is evident, as awareness of the machine is mostly restricted to areas near Bacong, while more distant locations, such as Dipaculao, remain largely unaware in the absence of connections between their social groups and those of the service providers. Moreover, many farmers with small areas of *laboy* soil, having dug canalets to drain water and worked the fields to aid decomposition, do not perceive the issue as significant enough to seek better solutions than those already available. However, the problem escalates during frequent rains, which overwhelm their canalets and cause the soil to revert to *laboy* conditions. At such times, demand increases, and the existing service providers are unable to meet the needs of all farmers.

The custom hiring service of the service providers is also an important part of a positive business case, as the machine is quite complex and expensive to manufacture, making it cost-prohibitive for a single farmer to invest in. Being able to earn from their clients' fields through service provision helps justify the investment as it increases the efficiency of the return on investment (Houssou et al., 2015). Furthermore, a better understanding of how the demand shifts could solidify the business case for prospective service providers. However, regardless of the possible returns, credit availability is still an important factor for the machine's uptake, which the soft loan facility of REMD provided (Cafer and Rikoon, 2018; Mottaleb et al., 2016; Verkaart et al., 2019). The adoption process could have scaled wider if there had been more focus on awareness and capability building among service providers of the surrounding areas of Bacong, like Dipaculao and Baler, which share similar conditions, seeing that these service providers are best positioned to profit from the relative advantage of the innovation should the constraints in awareness and up-front costs be bridged (Kuehne et al., 2011).

After the initial project, however, there had been no major concerted efforts for the scaling of the machine, where the scaling ingredients for collaboration, evidence and learning, leadership and management, and public sector governance are found to be lacking, which results in the machine not scaling widely enough, emphasizing the need for the involvement of other stakeholders in the agricultural innovation systems to realize scaling ambitions (Klerkx et al., 2012). Even so, we still find the machine in use today, due in part to another ingredient, altruism, that we find helps the innovation in scaling deeply that affects culture, shared norms and values, social relations, and trust with their roles in sustainable technology uptake (Carolan, 2006; Palis, 2006). Overall, these findings relate to the need for "facilitating conditions" for a technology to be accepted and used and, in the context of this research, to scale. As stated, the facilitating conditions do not seem highly favorable.

Looking at it more broadly, what is the implication of altruism in the larger uptake of agricultural technologies? The most obvious response is that farmers or end-users generally value relationships in addition to all the technical requisites of a machine. Farmers, at least in the case of the research participants, value human interaction, goodwill, and everything that is attached to it for them to embrace technology. This is an important point, as oftentimes, the promotion of machines is done routinely, with extension workers or any rural development workers completely detached from their intended technology recipients. The human dimension in agriculture should never be put on the back burner. The second important point is that altruism affects scaling in the sense that once the farmers have embraced the technology and are convinced of the altruistic acts of the developer or the extension worker, they will champion its use. Scaling will be an organic process that will be orchestrated by the farmers themselves. This argument is supported in the literature (e.g., Kiptot and Franzel, 2014; Nyanga, 2012; Akresh et al., 2011; Moore, 2015).

Going back to the framework, this finding on altruism could be seen in the light of 'social influence.' As reported, Doc Manny and his team frequently visited the farmers in Aurora and even worked with the farmers, so the latter acted as co-developers of the technology. With this, it is not difficult to think that Dr. Regalado became an 'important other' among the farmers in the area, especially with respect to his gesture of loaning the machine to the farmers even though they could not make any promise of repayment. As explained, these acts are important in Filipino culture, especially with the widely known value of '*utang na loob*' (cycle of obligations). With Doc Manny becoming an 'important other' among farmers, his championing of the technology certainly had an influence on them.

In UTAUT, Venkatesh et al. (2003) note that the effect of "social influence" is significant if the use of the technology is mandated. Hence, people may use the technology out of compliance. In the context of this research, the use of the technology was not mandated. The farmers, being research participants, could easily opt out of the research. More so, the farmers could easily abandon the machine after the research. Nevertheless, as we have reported, the machine remains in use and is considered the best technology in *laboy* fields more than 2 decades after its introduction. Hence, it strengthens the case of altruism as a key ingredient for their continued use of the machine.

To close this discussion, another aspect that needs explaining if one were to buy our proposal on altruism as another scaling ingredient is: why did the farmers trust Doc Manny and his team of researchers? In addition to Doc Manny being an 'important other' in the technology uptake, we argue that his approach to working with them facilitated the success of the process. As mentioned in the quote above, the farmers felt the warmth and kindness extended to them by a then stranger. The initial agenda of going to Aurora for the Palaycheck demonstration evolved to a second purpose of addressing the local concern on *laboy* production through participatory development, culminating in an unexpected altruistic gesture post-research agenda. As evidence that the gesture was no longer a research agenda when the *Laboy tiller* was left to be owned by the farmer, there is no monitoring record. This research only revisited the machine's life thereafter, two decades later. Kindness and warmth are highly valued in Filipino culture and even outside it. Brülhart and Usunier (2004) argue that perceived kindness matters.

Additionally, in the larger scholarship on 'trust,' "friendliness, openness, flexibility, and generosity" (Dent, 2005, p. 110) are among the key factors that build trust. Based on the narration above, these were all shown by Doc Manny and his team in their dealings with farmers. Thirdly, according to Dent (2005), trust is enhanced through socializing, and "communications of good will increase cooperation" (p. 107). As mentioned, Doc Manny and his group went back and forth to Aurora for several months, and they had productive conversations with farmers. Summing up the interaction between Doc Manny and the farmers, we argue that there was positive reciprocity on the part of the farmers. Brülhart and Usunier (2004) note that positive reciprocity combines trust and trustworthiness.

In the rural development literature, what Doc Manny and his team did could be said to be a part of the 'trust-building' phase. It could be. Nonetheless, whether it was a part of trust-building as a phase in rural development work or not, it is cogent that Doc Manny's gesture was felt deeply and positively by the farmer participants. To this end, we argue that the altruism proposal stands. Altruism is value-laden and multi-faceted. It could be seen either from the doer's perspective or the action's recipient.

6 Conclusion

We have seen that the *Laboy tiller* significantly impacted the lives of farmers in *laboy* areas. However, its highly specific niche, combined with the lack of concerted efforts addressing some key scaling ingredients, such as collaboration, evidence and learning, leadership and management, and public sector governance, placed much of the responsibility for scaling the innovation onto the beneficiaries themselves. This reliance limited the reach of the innovation to the boundaries of their social networks. Nevertheless, this situation also highlighted the critical role of altruism in the acceptance, sharing, and continued use of introduced innovations.

Going beyond the prescribed duties and obligations of a typical technology transfer relationship holds immense value. Altruistic intentions foster reciprocal tendencies among beneficiaries, often directed toward the benefactor. This elicits a relationship built on respect and trust, as beneficiaries reciprocate altruistic sentiments. Such a relationship, founded on mutual goodwill, enhances the productivity of their interactions, with the benefactor as an intervention implementer and the beneficiary as a farmer partner. Furthermore, when the transfer of innovation is grounded in goodwill, beneficiaries are more motivated to care for the received innovation, demonstrating their acknowledgment and respect for the benefactor's altruism.

Altruistic actions also extend beyond the direct benefactor-beneficiary relationship. Beneficiaries may feel a social responsibility to act altruistically toward their peers, thereby becoming benefactors themselves. This cascading effect enables the innovation to reach further audiences, albeit still within the constraints of the farmer-partner's social network. By fostering a culture of reciprocity and mutual support, altruism contributes meaningfully to the scaling and sustained adoption of innovations.

7 Notes

1 Sandro D. Cañete is a PhilRice agronomist.

2 Original in Filipino

> *"Technology nila noon mano mano. Ibinabaliktad lang noon ang damo. Dadamuhin hano pag walang tanim manual po yan na binabaliktad nila. Edi syempre buhay pa rin yung damo sa loob kasi binabaliktad lang nila."*

3 Original in Filipino.

> *"Ayaw na umabante kasi wala na po syang mahawakan ang gusto po nya meron syang kinakabig lagi. Di katulad nung floater (Laboy tiller) kahit wala na syang kinakabig na matigas o makunat tatakbo sya."*

4 Original in Filipino.

> *"Interviewer: Ano po ito yung spike. Parang maganda po ba na may spike or parang…*
> *Interviewee: Yan nga maganda.*
> *…*
> *Interviewer: Parang madurog talaga yung.*
> *Interviewee: Oo madurog nya yung mga dayami at damo. Kasi ang dating gamit namin wala parang tutumbahin lang yung kwan tutumba lang nya yung dayami saka damo."*

5 Original in Filipino.

> *"Interviewee: mahirap din nga. Mahirapan kasi ang kwan dyan kasi malaki sya mahirapan ang makina.*
> *…*
> *Interviewer: kung mas malaki po sya parang mas mahirap bakit po mahirapan yung makina?*
> *Interviewee: e maliban kung yung makina e lagyan mo ng mas malaki edi mas mabigat ka na naman."*

6 Original in Filipino

> *"Oo nagamit pa rin kasi pag yong alam mo naman yung lugar na malalim wag mo na padaanan ng handtractor paikutan mo na lang yon iwasan mo at pagka yung floating tiller na ang pifinish doon."*

7 Original in Filipino

> *"Pag marunong kang maghandtractor talaga marunong ka na rin."*

8 Original in Filipino.

> *"Interviewee: Maam kasi yung pagka masyadong maano yung tag ulan e yung kwan madali po kasi syang pag natubigan e lumulutang yung lupa.*
> *Interviewer: Pag tag ulan.*
> *Interviewee: Oo. Kahit na tag araw basta po umulan ng malakas umaangat sya parang organic ganon na parang bulok na lupa na magaan ganon."*

9 Original in Filipino.

> "Nang nagawa na ng kalsada dumami na ulit ang *laboy*."

10 Original in Filipino.

> *"Ang ginawa sakin ni Doc Manny iniwan nya yung floating tiller tapos irecord ko lang daw kung ano yung ginawa ko kung ilang pasada kung ilang gasolina yon ang irereport ko sa kanya pero walang bayad hindi nya ko sisingilin ng bayad kumbaga yung lang ang sasabihin nya sakin na nakailang araw ka nakailang padaan yung ginawa mo ganon ilang gasoline naubos mo. Ilang tao kayo mga ganon ang tinatanong nya sa akin. Kaya nung bandang huli baka gusto mo sabi nya hulug hulugan mo nalang e ang nangyari napunta sakin yung kauna unahang floating tiller na dumating dito sa Baler sa Aurora."*

11 Original in Filipino.

> *"Walang masamang komento puro magaganda kasi nakatulong nga basta nakatulong talagang laboy napaani naman nila kahit papano."*

Data availability statement

The datasets presented in this article are not readily available because of the participants' identifiable data embedded in the recordings. Requests to access the datasets should be directed to orcullolouiegerard@gmail.com.

Ethics statement

Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

JM: Conceptualization, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing. LO: Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing. TL: Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. The authors thank PhilRice for providing the funding for the conduct of this research under SED-232.

Acknowledgments

The authors would like to thank Ms. Camille C. Dumale and Mr. Mark Joseph R. Zuñiga for taking part in the data collection, as well as the Municipal Agriculture Office of San Luis, Aurora, for assisting in coordinating the data collection with the participants of the study.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 14 May 2025
DOI 10.3389/fsufs.2025.1542007

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OPEN ACCESS

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RECEIVED 09 December 2024
ACCEPTED 26 March 2025
PUBLISHED 14 May 2025

CITATION
Nettle R, Ingram J and Ayre M (2025) Digiwork: how agriculture 4.0 is changing work for farm advisers. *Front. Sustain. Food Syst.* 9:1542007. doi: 10.3389/fsufs.2025.1542007

Digiwork: how agriculture 4.0 is changing work for farm advisers

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Introduction: Advisers are commonly involved in supporting farmers navigate the smart farming transition, however their experiences in such roles, and any changes to their working lives, has not received a great deal of empirical attention. Knowledge about these changes would enable greater anticipation of disruptions to advisory work and help support strategies to maintain and build advisory capacity. This is important for stakeholders seeking to strengthen the advisory system as part of the Agriculture 4.0 era. This paper reports on a study of advisers in the UK and Australia who work with farmers in implementing Smart Farming Technologies (SFTs), to examine the ways in which their work is changing. Changes to the work of advisers is a less explored topic within smart farming yet is an important aspect to the way the Agriculture 4.0 is unfolding.

Method: We developed a multidisciplinary framework from the literature relating to work and working life to collect and analyse data with an overarching theoretical framing of advisory practice as socio-symbolic and socio-material relations. We interviewed 22 advisers and 4 Agricultural technology (AgTech) company representatives about changes to their work as their farming clients implement SFTs.

Results: Based on qualitative analysis of the interview transcripts, and applying grounded theory techniques of constant comparison, we found a range of changes to work including: the diversity of advisory roles; integration work or the emerging 'side office' at the nexus of the office and the farm; demands in work duration and changes in work efficiency and effectiveness; increased workload in learning and developing new knowledge and skills and in the work of building and adapting business models fit for smart farming.

Discussion: We discuss three contributions to the understanding of changes to advisory work: the evolution in advisory roles (including bifurcation and specialisation of roles) expanded knowledge brokering and intermediary work and digiwork, or the work of integrating social, material and symbolic practices in smart farming. These changes have implications for the functioning of the advisory system which, without collective support from government or industry, will privilege technology-centric, commercial and privatised advisory efforts.

KEYWORDS
consultants, digital agriculture, value-proposition, smart farming technologies, extension, advisory system, agricultural innovation system

1 Introduction

As a result of the fourth agricultural revolution, also referred to as Agriculture 4.0[1] (Klerkx and Rose, 2020), farmers and farm advisers are increasingly involved in managing the proliferation of new technical devices, new forms of information and new knowledge and networks that produce digitised representations of farm performance and changes to agricultural processes interconnecting different systems and actors in the agricultural value chain (Ayre et al., 2019; Charatsari et al., 2022; Maffezzoli et al., 2022). The Agriculture 4.0 term encompasses the technologies, socio-cultural and socio-behavioral practices of actors in the agricultural innovation system (Klerkx et al., 2019) and incorporates precision farming, smart farming and digital agriculture. The issues faced by farmers in this transition has received a great deal of attention (e.g., Tey and Brindal, 2022; Giua et al., 2022), however the implications for farm advisers have been less of a focus, despite their role being described as key 'sensemakers' for farmers (Eastwood et al., 2017). Studies have identified a range of roles and challenges for advisers in the context of smart farming. For instance, farm advisers are considered key in the adoption phase of technologies, helping with farmer decisions and guiding the process, either as generalists across all areas of farm management (for instance as agronomists, farm management consultants, extension officers, farm input suppliers, veterinarians) or as smart farming and digital agricultural specialists (e.g., remote sensing and data interpretation) (Klerkx et al., 2019). The disruption to farm advisers from new actors such as software developers, data analysts and Ag-Tech specialists has also been acknowledged (Wolfert et al., 2017; Ingram and Maye, 2020; Ingram et al., 2022a, 2022b; Klerkx, 2020, 2021). However, the potential changes for their work patterns and routines and professional identities have only more recently come into focus (e.g., Bryant and Higgins, 2021; Charatsari et al., 2022).

While it is acknowledged that technologies are contributing to a reorganisation of the labour process in agriculture (e.g., Prause, 2021), the changes to the roles and work of advisers and the experience of advisers in this transition have not received a great deal of empirical attention. Where studies have been undertaken, the emphasis has not been directed to the overall changes to work, but has focused on changes to professional identities (Charatsari et al., 2022), changes to the farmer-adviser relationship (Dockès et al., 2019; Eastwood et al., 2019) or advisers' 'digi-grasping' (i.e., how advisers handle uncertainty and understand their roles in agricultural digitalisation) (Rijswijk et al., 2019) including navigation of 'digiware', that is, the socio-material changes of digitalisation for farm advisers (Ayre et al., 2019). Farm advisers' knowledge-brokering and intermediary work is also recognised as increasingly important in the context of these transitions and critical in helping farmers and technology developers manage the uncertainty and complexity of these transitions (Klerkx et al., 2019; Klerkx, 2021). Given the critical role advisers play in facilitating on-farm change and the uncertainty regarding new roles and disruption to the advisory system, it is important to understand the lived experience of farm advisers in supporting farmers' implementation of smart farming technologies and how work is changing for them. Our interest in the work of advisers stems from this, and the responsible innovation agenda, which calls for better anticipation of the social and ethical dilemmas associated with the emergence of Agriculture 4.0 (Eastwood et al., 2019; Lioutas et al., 2019; Lioutas and Charatsari, 2022; Rose and Chilvers, 2018).

This paper reports on a study of farm advisers who work with farmers in implementing Smart Farming Technologies (SFTs), to examine how their work is changing. In this paper, we apply the definition of SFTs provided by Balafoutis et al. (2020) being the application of autonomous systems and information and communication technologies (ICT) into agriculture, such as variable rate applicators, Internet of Things (IoT), geo-positioning systems, big data, unmanned aerial vehicles (UAVs, drones), automation and robotics. While Agriculture 4.0, being considered a system-level transformation, provides the context for our study, we focused on smart farming technologies to ground our study in the everyday work of farm advisers and their engagement with the technologies implemented or demanded by farmers. The study was conducted with advisers in the UK and Australia where they are actively engaging with SFTs. The next section reviews the literature articulating various visions of the smart farming future for advisers and changes in advisory roles. In studying the changes to advisory work, we seek to contribute to knowledge and the theorisation of the unique and important role and practices of farm advisers and farm advisory systems in the Agriculture 4.0 context.

2 Expected advisory changes with the transition to agriculture 4.0

Changes to advisory roles and responsibilities in smart farming are predominantly suggested to be toward greater specialisation, with field and farmer-facing 'front office' roles and remote or on-line 'back-office' roles such as in providing remote sensing or farm data analytic services from afar (Laurent and Labarthe, 2013; Rijswijk et al., 2019; Klerkx, 2020, 2021). Such changes are suggested to bring new responsibilities and changes to professional trajectories and professional identities (Charatsari et al., 2022). With respect to specific changes in the work of advising, Ayre et al. (2019) report greater focus on data collection, organisation and interpretation, with advisers having to make complex hardware and software investment choices, determine the value that technology offers for farmers and consider the broader sustainability issues of digitisation (Ayre et al., 2019; Cook et al., 2022). The symbols, materials and social roles and relationships that farmers and consultants employ and manage to gain benefit from digital tools and technologies was termed 'digiware' by Ayre et al. (2019) to distinguish an innovation category in digital agricultural contexts. This change is reported to bring new forms of knowledge, and new demands on data interpretation, with advisers needing to understand the functions and processes behind the working of digital technologies and data processing practices, a shift further elaborated by McCampbell et al. (2022) and Ingram and Maye (2023) in their studies related to digital rights and capacities for digital agriculture.

1 Agriculture 4.0 refers to a set of sophisticated technologies, like the Internet of Things, Big Data, Artificial Intelligence, machine learning, decision support systems, blockchain technologies and remote sensing. Encompassing terms such as 'digital agriculture', 'smart farming' or 'data-driven farming' (Klerkx and Rose, 2020).

Another area of change is suggested to be the new relationships advisers are making or need to make with new partners and in changes to communication patterns with farmers (Rijswijk et al., 2019; Fielke et al., 2021), with farm advisers playing a double-mediating role of adviser-advisory work and adviser-farmer relationships (Klerkx, 2020). Farm advisers are therefore fulfilling 'process intermediary' or 'user intermediary' functions (Kivimaa et al., 2019, p 106) translating and interpreting technology attributes for farmer preferences and working both with technology developers and farmers to qualify the value of technology offers at an individual farmer or project scale. Such activities can extend to knowledge brokering when they enable knowledge flows between different technology developers and farmers (Klerkx et al., 2012). It has been suggested that with these roles there is potential for greater occupational stress whereby the time saving in (for instance) remote monitoring of the data of farm clients may be outweighed by the threat of big organisations replacing their advisory role (Charatsari et al., 2022). While change to advisory work practices and routines and the creation of new roles is considered critical to support farmers in dealing with new uncertainties (Bryant and Higgins, 2021), there is limited detail about these changes. A greater understanding of the changes to work for advisers is therefore critical to how the implementation of SFTs is better supported.

Further, advisory knowledge, skills and competencies change. It has been found that with SFTs comes a need for advisers to place greater emphasis on farmers' needs assessment, facilitation, intermediation and value generation (Charatsari et al., 2022; Reichelt and Nettle, 2023). These authors argue that the Agriculture 4.0 transition creates gaps in competency, including that of working with ethical challenges such as where data and technology are considered more reliable than human advice. This is balanced with recognition that the traditional duties of farm advisers remain, in offering tailor-made advice and products to their clients (Rijswijk et al., 2019; Charatsari et al., 2022, p. 350). However, the extent to which advisers are challenged in their work to balance traditional advisory roles with smart farming transitions is not well understood, yet these changes have implications for the day-to-day work of farm advisers and the experience of those working in new roles in smart farming. Changes to advisory work has been acknowledged in the domain of farmers' sustainability transitions such as to agroecology (Coquil et al., 2018). The research reported in this paper seeks to add to current knowledge on the changes to work that are enabling and constraining the application of SFTs. The research question guiding the study is: *How is work changing for advisers in the UK and Australia when supporting farmers to implement SFTs?* Our objective is to consider the implications of changes to advisory work in the context of the challenges and opportunities of the Agriculture 4.0 transition. In this paper we show that the work practices represent a particular function and role for advisers in smart farming, being that of knowledge integration.

2.1 SFTs and the advisory system in the UK and Australia

We chose the UK and Australia to conduct our study as governments in both countries envisage an agricultural transition underpinned by SFTs. They share similar timelines and trajectories both with respect to implementation and strategies for fostering public and to private collaboration and investment in research and development across key sectors (Agri-Tech Centre, 2024; Department of Agriculture, Water and the Environment (DAWE), 2022). Both countries have a privatised agricultural knowledge and innovation system (AKIS) and seemingly limited outward support to advisers in this transition, despite the new demands on advisory work and skills shortages (KPMG, 2019). The implications for advisers' work are just becoming apparent in both countries (Ayre et al., 2019; Ingram et al., 2022b).

This section outlines the support to Agriculture 4.0 in both countries and the role of the advisory sector in contemporary agricultural transitions.

2.1.1 UK: Innovate UK and the transforming food production challenge

As part of the UK government's agricultural transition plan post-Brexit (Downing et al., 2018), there has been a focus on creating an enabling environment of funding and support to help businesses, researchers and industry to transform food production, including promoting the development and use of new technologies on-farm. Through Innovate UK, the government established the UK Agri-Tech Centre. The Centre supports partnerships between farmers, advisers, researchers, and technology companies to accelerate the deployment of SFTs (Agri-Tech Centre, 2024; CHAP, 2024). While the Transforming Food Production Challenge Fund Programme (UKRI, 2023) has invested in collaborative projects which focus on productivity, reducing the environmental impact of farming (biodiversity, water, nutrient management), and catalysing net zero. SFTs for on-farm monitoring for compliance with supply chain standards is a further driver. More generally, digital literacy is being promoted in the wider workforce, with local skills improvement plans (LSIPS) developed to assist further education providers align their efforts to sectoral needs, including in agri-tech (Business West, 2024).

Efforts to support farm advisers in their role, or with supporting the development of knowledge and skills. Are largely absent in the AKIS in the UK. Despite this, advisers are increasingly taking up roles as intermediaries and knowledge brokers in smart farming projects involving farmers and technology companies or as part of the government's Farming Innovation Programme. With a privatised, fragmented and devolved advisory system system (Prager and Thomson, 2014), advisers' experience of SFTs across the UK are variable. Some might be engaged in research projects assessing or using SFTs. While others, employed by larger consultancy or input suppliers, will use proprietary SFTs and have in-house support. However, there is no overall government program of support for building adviser skills related to SFTs.

2.1.2 Australia: supporting start-up companies and digital agriculture strategies

In Australia, national government investment to support research and development into smart farming technologies and practices is made via the rural research and development corporations (Rural R&D corporations, 2024). A national Digital Agriculture Strategy (Department of Agriculture, Water and the Environment (DAWE), 2022) seeks to support the adoption of digital technologies through: improving digital infrastructure (e.g., the National Broadband Network (NBN) support to IoT devices for data collection); data management; and access to technology for farmers. The National Farmers' Federation's (NFF) in Australia has developed a farm data

TABLE 1 A conceptual framework to consider work changes for advisers in supporting SFT implementation.

Concepts in understanding advisory work	Key Authors	The interpretation and application of the concept in this study
1. Workload	Warhurst and Knox (2022); Eastwood et al. (2017)	The amount of work in a given period, the overall duration of work and the intensity of work including the demands required to complete work tasks. We include physical, cognitive and affective aspects of work including learning load or the time spent learning and gaining new skills… Workload is linked to the working conditions and job quality of advisers.
2. Work organisation	Laurent and Labarthe (2013); Eastwood et al. (2019).	How work is organised including specialisation in job roles such as the front and back office or changes to established work routines such as engaging with farmers remotely rather than farm visits.
3. Professional identity	Charatsari et al. (2022); Nettle et al. (2018); Rijswijk et al. (2019); Gosetti (2017).	Including subjectivity and emotions in work and the meaning of work. This includes quality of working life and aspects such as stress at work, work satisfaction, work recognition, self-determination and autonomy in work, feelings of coherence in work.
4. Knowledge brokering work	Klerkx et al. (2012); Klerkx and Leeuwis (2008).	Activities and processes to exchange and translate individual knowledge stocks into shared knowledge. The work involves actors facilitating connections, enabling coordination and creating opportunities for learning.
5. Intermediary work	Klerkx and Leeuwis (2008); Kivimaa et al. (2019)	Relates to the role of advisers in the agricultural innovation system between users and producers of knowledge. They can be 'process' or 'user' intermediaries (Kivimaa et al., 2019, p 106) in translating and interpreting technology attributes for farmer preferences and working both with technology developers and farmers to qualify the value of technology offers at an individual farmer or project scale.
6. Knowledge, skills, competence	Eastwood et al. (2019); Ingram and Maye (2023).	Workforce qualifications and experience, and changes to skills arising from SFT's including iterative processes of adapting and integrating digital tools and services and interpreting and hybridising with their own knowledge. There is overlap with workload (learning) load.

code (NFF, 2023) and strategies to guide government policies and industry initiatives in technology and innovation in agriculture to improve productivity, sustainability, and resilience. There is a range of government support to enable and promote agri-tech entrepreneurship including technology incubators and accelerators for new agri-tech ideas (Renando, 2023). This is further supported through national platforms and events to bring researchers, technology companies and farmers together with potential venture capitalists (i.e., evokeAG and growAG) (AgriFutures, 2024).

Some Australian State governments provide support to technology companies and farmers to work together to trial solutions such as in Internet of things (Agriculture Victoria, 2024) and there are targeted grants, subsidies, and tax incentives to farmers and agricultural businesses for adopting smart farming technologies and practices such as in offsetting the initial costs of implementing new technologies. A recent report commissioned on the digital capabilities of the Australian agricultural workforce identified a need to increase the 'digital maturity' (KPMG, 2019, p. 7) of Australian agriculture and identifies the application and management of digital data in farm production as a significant issue and where a critical capacity is required (ibid).

However, there is no overall government program in Australia for building adviser skills related to SFTs. The Australian pluralistic agricultural extension and advisory system involves diverse government, commercial and public/private actors (Nettle et al., 2021), and there is fragmentation in support to smart farming (Fleming et al., 2021). There is also a dependence on farmer organisations or professional associations to support advisers in building smart farming capacity and capability (e.g., Crop Consultants Australia, 2024).

3 Conceptual framework

To understand the roles and functions of advisory work in the Agriculture 4.0 era and the application of SFTs, we developed a conceptual framework to structure data collection and analyse empirical data from interviews with advisers. This framework is multidisciplinary, combining theories and frameworks from agricultural innovation systems and the study of work and quality of working life, consistent with an understanding of advisory practice as socio-symbolic and socio-material relations (Ayre et al., 2019; Higgins et al., 2023). Key concepts are summarised in Table 1.

4 Methods

We chose a qualitative approach to examine the subjective experiences of advisers and their work with farmers who had implemented any or multiple SFTs, with a view to examine how their work was changing. Our first selection criterion was to include advisers from across the main farming sectors in both countries (arable/broadacre farming, mixed farming crops and livestock), livestock farms (sheep, beef or dairy farms) and horticulture, and the second criterion was to include advisers with experience working with farmers with respect to their implementation of SFTs. We also sought to include advisers who represented a diversity of business types including: independent advisory businesses, rural resellers; commercial adviser companies, technology companies, public-sector, industry bodies and not-for-profit organisations. As advisers were recruited, we monitored the emerging demographic profile to ensure gender and age diversity. Advisers from the UK and Australia were recruited through a combination of key informant networks of the authors (UK and Australia), a farm consultants' association (Australia), snowball sampling (Parker et al., 2019) through primary respondents, and a public call in the UK, circulated through newsletters of agricultural organisations, inviting advisers to register interest in participating in the research. The call for participants included photos of different technologies used on farms and the heading: *Are you a farmer or adviser using smart tools and technologies (precision farming, sensors, robotics, data tools and automated systems)?* Followed by wording: *We would like to hear from farmers and advisers about their experiences using smart/digital tools and technologies. For more information, please leave your contact details [google form] and a researcher will be in touch.* Information about the researchers and their organisation affiliation was also provided. A google-document format was used so that interested respondents could provide their information privately. A link to the public call is provided in the Appendix.

The sample of interview respondents is summarised in Table 2. The research received human ethics approval from the University of Melbourne, Australia (ID Number: 26115 and ID Number 21284).

Semi-structured interviews with 22 advisers (7 in Australia and 15 in the UK) and 4 AgTech company founders (3 in Australia, 1 in UK) were conducted between 3rd March and 6th June 2022 (Aus) and April 15–July 15, 2023 (UK). Interviews were conducted over Zoom and by phone. Interview questions covered the adviser's work history and context for working with farmers, the nature of their work with farmers, how this had changed and anticipated future changes. We did not collect information about the advisers' salaries, income, or other benefits received or how this had changed with respect to their work in smart farming. However, we note that specialist advisers tended to work more in commercial companies and with the broadacre/arable farming or horticulture sector where the use of drones or variable rate technologies and precision agriculture and data driven decision-making was more prevalent. On the other hand, the livestock sector had more public sector, industry or independent farm management consultants supporting farmers with smart farming technologies like cow collars or robotic milking.

Advisers fulfilled varied roles in providing support to farmers including as generalists (18 advisers, including independent agronomy businesses, farm management and livestock consultants, farm input suppliers, project facilitators, public sector advisers) and specialists (8 advisers or companies specialising in smart farming, including remote sensing and data interpretation). Fifteen advisers were male, and 7 were female, and advisers worked across the arable farming (cropping/broadacre farms), livestock (sheep, cattle, dairy) and horticulture (fruit and vegetables) sectors (Table 2.)

Interviews were audio-transcribed and analysed to generate themes about the features of work-related changes for advisers in supporting farmers to implement SFTs. Qualitative data was coded using NVIVO™ software by applying the conceptual framework (see Table 1) whereby text was coded to the dimension of work category to which the content was most closely aligned. Codes included: 'adviser perspectives of SFTs'; 'adviser roles'; 'adviser skills'; 'back-office work'; 'frontline work'; 'farm service models'; 'intermediary work'; and, 'training and education'. Text in each of these categories was then reviewed to examine the patterns and interrelationships within and between each category, including discourse related to challenges or opportunities from changes in work and how these are framed. We applied a descriptive rather than critical lens (Gee, 2011, p. 8) and, consistent with our inductive approach, adapted analytical techniques from grounded theory, including a constant comparison method, whereby each interview was coded and compared to the following interview text to test for fit (or deviation) between the data and the emerging categories, and to test the fit between the emerging concepts and processes and new data coming from additional interviews (Charmaz, 2024; Charmaz and Thornberg, 2021). In the following results section we present the key themes from this analysis. We use the generic term 'adviser' or 'consultant' to describe the participants, except where they are digital agriculture specialists and have SFT expertise.

5 Results

5.1 Smart farming technologies used by advisers in their work

The advisers in this study noted they used a range of smart farming tools and technologies in their advisory work (Table 3), illustrating a diverse scope of application across different agricultural sectors. Most advisers and companies were also developing their own smart farming tools and services. These bespoke tools and services ranged from software platforms developed in-house by large commercial agronomy companies for their advisers, to excel spread sheets created by individual advisers as a way of integrating data systems.

5.2 Diversity of advisory roles in supporting smart farming technologies

Participants in the study described different roles in supporting farmers to decide on and implement SFTs. Some described their role as precision agricultural experts or specialist consultants. Their consultancy business model was based on charging clients for these services and this in turn affected the type and extent of smart farming expertise offered as part of the service delivery:

> *'So, I've worked in precision farming for 16 years now, mainly looking at soil nutrition. That's sort of where I started out, and where our main focus is …still soil nutrition….remote sensing, satellite sensing, looking at variable rate nitrogen, looking at intelligent field walking…crop scouting' (UK, Adviser 17).*

Other role descriptions included: an agronomist or generalist farm adviser; consultants who work independently or with these specialists to provide better advice to clients or worked with technology developers to validate or improve their products. These roles were about giving confidence to their clients if they wanted to take on smart farming products. They saw their role as intermediaries in the smart farming transition, and highlighted the importance of working together with farmers and specialists:

> *'You've got to get a few people working together… the grower… the agronomist… a precision agriculture expert that does all the maps. And it's just getting all that to crossover at the right time. And then make sure they [the grower] can implement it… and it's all going to work' (Australia, Adviser 2).*

TABLE 2 Adviser roles, advisory organisations and interview details for this study.

Adviser Code	Advisory Role	Business Type	Location	Interview Date
Adviser 1	Agronomist (cropping)	Independent agronomy business	Australia	09/03/22
Adviser 2	Agronomist (cropping)	Farm input reseller	Australia	10/06/22
Adviser 3	Agronomist (cropping)	Farm input reseller	Australia	03/03/22
Adviser 4	Agronomist (cropping)	Independent agronomy business	Australia	23/11/22
Adviser 5	Agronomist and digital agriculture consultant (cropping)	Independent agronomy business	Australia	18/11/22
Adviser 6	Agronomist (cropping)	Independent agronomy business	Australia	14/02/23
Adviser 7	Agronomist (cropping)	Independent agronomy business	Australia	18/11/22
Adviser 8	Agronomist (cropping)	Large private company providing advisory services	UK	02/05/23
Adviser 9	Horticulture consultant	Large advisory and research consultancy /Public advisory service Wales	UK	12/05/23
Adviser 10	Agronomist (cropping)	Large private company providing advisory services	UK	12/06/23
Adviser 11	Horticulture consultant	Associate of research institute	UK	07/06/23
Adviser 12	Dairy	Public advisory service Wales	UK	19/05/23
Adviser 13	Agronomist (cropping)	Large private company providing advisory services	UK	24/05/23
Adviser 14	Independent farm management consultant, dairy/livestock	Solo operator	UK	11/05/23
Adviser 15	Independent farm management consultant, business and finance dairy/livestock	Large private company providing consultancy, policy and research services	UK	3/05/23
Adviser 16	Agri and Environment Consultant, livestock	Large private company providing advisory and research services	UK	9/05/23
Adviser 17	Specialist adviser (remote sensing and precision agriculture)	Large private company providing farm inputs and advisory services -	UK	17/05/23
Adviser 18	Intermediary /facilitator for a AgTech project in the livestock sector	Environmental Management company	UK	3/05/23
Adviser 19	Livestock technologist	Public advisory services	UK	10/05/23
Adviser 20	Project manager, digital value chains (livestock sector innovation, skills and capabilities).	Education and research organisation	UK	19/06/23
Adviser 21	Independent consultant, livestock technologies	Solo operator	UK	21/06/23
Adviser 22	Adviser and educator	Education and research organisation	UK	26/5/23
Company 1	Livestock AgTech	AgTech company founder	Australia	13/4/23
Company 2	Robotic company (horticulture)	AgTech company founder	UK	2/5/23
Company 3	Grazing AgTech Company	AgTech company founder	Australia	4/5/23
Company 4	Insurance AgTech start-up	AgTech company founder	Australia	23/8/23

This role advisers fulfill of being an intermediary was considered a role for generating trust in technologies with farmers:

> *'If you have built up that relationship, that trust there, between you as the consultant and the grower, they tend to trust if you think that that technology's going to offer a reasonable response in service' (Australia, Adviser 6).*

When trying to bring in technology specialists, generalist farm advisers noted some challenges with calling on this expertise which included aligning work schedules:

> *'You've got to get the experts in. I'm not the expert on everything, so sometimes I have to get other advice to get it to work. And then there are issues. Everyone is so time poor these days…' (Australia, Adviser 2).*

Some advisers who were part of farm input supply firms or technology company staff described their role as 'spending time in the office' (UK, Adviser 17, see below) which included remote sensing specialists, software developers including coders and producers of dashboards and software engineers. There was a delineation between 'field roles' and 'office roles', with 'office roles' mainly being remote

TABLE 3 Summary of smart farming technologies used by advisers.

Type of Tool or Technology	Application/s and sector	Tools and Technologies Used by Advisers in this Study
Spatial data management (Geospatial Information Systems)	Assessing and predicting crop production dynamics and	Precision Cropping Technologies (PCT-AgCloud®) is a geospatial data management platform. Satamap® is a web-based platform for accessing satellite imagery globally. CERES Imaging® uses satellite and other data to predict plant growth and manage risk to crop health
General farm production data management	All sectors	Excel® software is used for data organisation and management. Farmplan ™ is a farm management and data software program. Agworld®is an integrated data management system for farm management. Muddy Boots ™ is a cloud based software platform that supports crop production and data management. Omnia Digital farming® is a software tool that enables customised farm mapping for soil and carbon mapping
Hardware and equipment	Equipment for precision applications and monitoring of inputs	Automated tractor steering and data collection (e.g., Trimble®, Geographic Positioning Systems) Precision seeding technology Soil moisture probes (sensors) Drones Camera sprayers Canopy sensors Soil temp sensors with LoRaWAN (long range wireless area network)
Hardware-livestock	Livestock management and monitoring	Gallagher HR5® electronic identification tool for livestock CowManager ®
Specific agronomic decisions	Crop disease predictions and crop management	Predicta B ® is a digital soil testing service that quantifies the amount of soil-borne pathogen DNA. Soilmate® is a software program that supports soil and plant nutrition agronomy. Yardley® Eu app https://horizon-openagri.eu/open-source-catalogue/soilmate/ WEED-IT® is a digital weed detection technology to support efficient herbicide application. Garford Robocrop-® computerised in row weeder Rootwave ® electric dock weeder
Farm operations and planning	Production systems and project management	Trello® is a visual work management tool. Terra Map ™ is an app for navigation and accessing geographical data. Terra Plus ™ is an app that supports soil data management.
Seasonal and weather forecasting	Cropping and other production decisions	Bureau of Meterology (Australia) app provides current and historical climate data and outlooks. Cli-MATE ® is a tool that analyses long term climate data and trends.

sensing, GIS and data oriented. For instance, a remote sensing specialist described his office work:

> *'… my role has gone from being very field-based to very not field-based anymore. I spend a lot of time in the office. Building the respect of our sales team…an agronomist rang me … "There's some patches in a crop…. "they suspect it might be a pH issue, … So I've said, "We'll just take some remote sensing data. We'll have a look at if we can see it from satellite data, then we'll just give you the satellite data"…' (UK, Adviser 17).*

Field roles were also covered by a diversity of advisers, for instance in the supply of digitally enabled weather stations, where the role included installation, monitoring, servicing and data support. A consultant in Australia described how they assessed the moisture variation in a large paddock with satellite imagery and altered the planting density based on different moisture zones. This generated a large saving in seed costs. In another example, satellite imagery was used to plan the timing and process of cutting hay from a canola crop to maximise economic gain. In the last 10 years or so, with tablets and mobile phone technology and interconnectivity, there has been a lot of progress in the usefulness and applicability of smart farming technologies to decision making, despite ongoing issues with accessibility in many regions in Australia, as one consultant in Australia noted:

> *'About 10 years ago I'd say, there was a definite change … and people had connectivity outside the office, then things really started to ramp up and we are definitely being hamstrung now by just not being enough connectivity to allow a lot of these things to do what they are supposed to do…' (Australia, Adviser 1).*

Facilitation roles of advisers were also more common in Wales in the UK, where there has been government investment in supporting interactions between growers, adviser and technology developers:

> *'I'm not an IT whiz … I'm much more about providing farmer support … and then bringing in the services that I need, so I learnt loads about livestock tracking. I was there to help farmer groups trial novel ways of working within their farm businesses… an innovation broker they called us. I'm an agricultural consultant. There's an acknowledgement in Wales, in order to make these … farmer-led projects happen, they all needed facilitation services' (UK, Adviser 16).*

Some advisers were working to fill a gap in providing support to farmers in working better with what they already had in the way of technologies, rather than suggesting or promoting new technologies.

> *'There's no one doing what we are doing …working with predominantly the … proven technologies, …I'm still being faced with farmers … that aren't using any form of what you'd define as agritech. … people thought that farmers were against or tech averse. That's actually not the case, they are completely open, they just need to be shown and have that conversation' (UK, Adviser 22).*

5.3 Integration work

The role of advisers in performing integration work was described by respondents as addressing two main integration challenges: (1) the integration of new and existing technologies and data into current farming practice and; (2) the integration of different equipment, digital data and digital tools and/or platforms for functionality to address interoperability issues and support farm decision making.

Many consultants described creating their own solutions for integrating digital information and data sources for their clients. For example, some respondents have developed tailored spreadsheets (for example, in Excel®) to manage digital data from different sources and produce reports that can be used in discussions with clients.

> *'…our consulting side of things, we do not use any of the technology, we just create our own platform… create our own spreadsheet' (Australia, Adviser 6).*

Farm advisers in both countries noted the importance of software products that they and/or their clients used as integrative platforms for farm data. In Australia, Agworld®® was described by some as a 'game changer' for their consultancy service provision (Consultant 2) with the ability to combine data in a single place and provide a 'history of the paddock all in one spot' (*Ibid.*), providing an historical record of farm characteristics and performance (i.e., yields). Common farm management software platforms in the UK included Muddy Boots ™ and Farmplan ™, however advisers noted that new software products were often not compatible with these. Advisers also mentioned that some standardised data platforms were proprietary owned, meaning only clients of a particular company could have access to the platform.

Farm management consultants also described working with technology developers to understand the tools being offered so that they could discuss features and benefits with their clients, which was then influencing the level of trust in the tools by farmers:

> *'… if it's a trust thing, they'll [technology developer] try to highlight how the data goes through [and is created and stored], so that we [consultants] know that the data is true and legit' (Australia, Adviser 1).*

Part of the adviser's work with technology and software developers was to encourage developers to work with what farmers were already using:

> *'…what they [farmers] do not want is new bits of software coming in that they then have to start using. What they really, really want is for everything to be seamlessly linked' (UK, Adviser 11).*

Overall, much of the work of the generalist advisers was to help the farmer integrate data and use the diversity of equipment and data sources to better effect, as described by both Australian and UK advisers:

> *'…a bit of a frustration is that they might have spray records on their tractor, they might have a weather station on their farm, they might have sensors in their grain store, they might have satellite imagery they want to utilise, but yet they are having to use all five, six different systems to view all that information. And we cannot find anybody who just wants to invest the money to bring that all into one place (UK, Adviser 17).*
>
> *'There's that many different technologies you can provide [to farmers], companies coming through with different things, that the challenge is getting it to integrate together, talk together, to have one base, essentially' (Australia, Adviser 6).*

Two other advisers described their role, and the challenges, in the integration of different digital technologies:

> *'The other challenge is the integration between, and the flow of data from, one business to another, or from one app to another app, or from one support tool to another support tool' (Australia, Adviser 1).*
>
> *…it's just kind of navigating that [smart farming] space. There's so many different platforms and programs and things that do not all talk to each other (Australia, Adviser 2).*

Generalist advisers and farm consultants suggested that by performing this integration work and using SFTs themselves, they were contributing to efficiencies in farming:

> *'… I do see agri-tech [agricultural technology] as being more for us as advisers than for the farmer…they get us to do it [the data interpretation]…. More and more, they are overwhelmed, just trying to do the basics of farming' (UK, Adviser 8).*

5.4 Increasing work efficiency and effectiveness and workload

Respondents highlighted the time commitment required to trial and adapt new tools and technologies, as well as invest in skills development in data management and analysis techniques. The workload for advisers, mainly in work duration or time spent, was associated with developing the capacity to assess what the various capabilities of tools/technologies are, and then how to integrate them in ways that support farm decision making. One adviser described this experience:

> *'You have to know how to pull it all together into one place and have a place to put it. I think that's a massive challenge…and it's time consuming' (Australia, Adviser 5).*

For tools and technologies to support the consultancy relationship, they must provide not only opportunities for time saving on the part of the consultant, but also direct decision support for productivity gains for the farmer, as one adviser explained:

> *'... to me the only thing that can help me is the time it takes. If I can do something so much quicker, more efficiently than I could in the past, well that's what helps our business. Or if it [tool or technology] helps the grower, then it helps the grower and if it can do both those, if it makes my time quicker and helps the grower, then it's a win-win' (Australia, Adviser 1).*

Another adviser described the way they had integrated drone services into their advising role in the horticultural sector to create efficiencies across all their work areas:

> *'We use it [drone technology] for our trials department. We use it for things like black grass mapping, insurance claims. We use it for fruit sectors…so we ... count blossom clusters…we look at vigour… the fruit sector is where that [drone technology] really comes into its own' (UK, Adviser 17).*

Assessing the value of tools or services remains a challenge of consultancy businesses with advisers reporting that they receive minimal or delayed support from technology developers. This included delays in getting service support:

> *'…the serviceability on such [technology] products. If something broke down, you are out here [in a remote area]. To be honest, you cannot afford the few days to wait to be fixed. Then it depends if you can call upon the expert [that] is four hours away ... -and then whether there's a problem that can be talked through, or a problem that needs to be addressed by the service provider' (Australia, Adviser 6).*

5.5 Learning and developing new knowledge and skills: workload implications

A key dimension to the work of advisers in smart farming is learning and developing new skills and knowledge that expands their traditional roles which adds to their workload. Advisers commented that they can spend considerable time teaching themselves how to access, run and integrate software programs and associated costs can sometimes be high for smaller consultancy businesses or sole operators. In contrast, larger agricultural service providers, such as rural re-sellers, arguably have a greater ability to absorb some of the costs associated with trialing and using new tools and technologies as part of their services.

Several respondents identified that the range of specialist skills required to provide consultancy advice in smart farming exists on a spectrum from expert field-based knowledge of the farming systems context (i.e., agronomic expertise) to proficiency with analytical and integration techniques using digital tools and technologies. Some advisers emphasised the value of connecting and communicating with others in their professional networks to source specialised advice, for example:

> *'…it's always good to get other consultants' points of view too… if they have dealt with it [a tool/technology] or had experience with it' (Australia, Adviser 6).*

Whereas people in large companies providing technologies and services to farmers had access to in-house training and development, most of the independent advisers or sole operators interviewed described being self-taught and with no or limited access to training in smart farming:

> *'So, I am not qualified [in digital agriculture tools and techniques] ... I've built knowledge over time. So, I've adapted to ... what growers want, what [digital] technology is out there—I've developed with it, ... when satellites first came out, ... data was a real challenge to deal with [I've learnt it] ... reading tutorials about QGIS and then reading peer review papers ... picking that up and making it mainstream' (UK, Adviser 17).*

Advisers working in smart farming contexts noted that they spend a lot of time working independently to learn about various tools and software, including learning new concepts, data collection practices, curation and analytical techniques, as well as digital systems (i.e., software systems). Many tools and programs are updated regularly which also means that it is a challenge for them to keep up with changes, particularly when they may only use a tool/technology annually based on the production cycle (i.e., to assess crop yield):

> *'I think it's a massive challenge—learning all these different bits of software…there are no real shortcuts…not unless you know someone that's willing to sit down and teach you how to use it' (Australia, Adviser 5).*

The time spent was necessary because it was about the adviser being confident and capable in oneself and knowing the technology or product well enough to be able to recommend it with confidence to clients. For example, one consultant explained:

> *'I do not really like recommending [a tool/technology] unless I can understand it fully myself, personally, from my personal experience as a consultant ... as long as it's got advantages that outweigh any of the risks associated, or the cost effectiveness of it' (Australia, Adviser 6).*
>
> *'However, this time commitment can be difficult to justify in some circumstances, as one respondent noted: I think if you were a field agronomist, you would find it [the time commitment to learn] very hard to justify…and how to charge for that [new tool/technology/service]…' (Australia, Adviser 5).*

Some advisers struggled to see a benefit to spending time on learning about new tools/technologies:

> *'If we do not have the time to do it [use tools/technologies] well, then we are not doing it. It's like when drones first came out…we cannot charge the grower for that. Because they can go and buy the drone themselves. So, if we cannot add value to what we are already doing by using it [a drone], then we cannot do it' (Australia, Adviser 4).*

However, other advisers reported saw the benefits of investing time in improving their software skills in developing and delivering effective advisory services:

> *'…what I sell to them [farmer clients] is my advice and the value of me. And if software can make me more valuable and more successful…' (UK, Adviser 8).*

Some consultants interviewed noted that learning about the benefits of new tools and technologies can be constrained by the need to pay to use them before trialling or testing them for example, subscriptions to new software programs. Currently, the cost of some tools/technologies can also be prohibitive for some consultancy businesses and their clients. This can restrict the ability of consultants to experiment and try new tools/technologies. In some cases, short term trials of tools/technologies are offered by software developers, however this is not enough time to know if a tool/technology is a good fit or can add value to a consultancy service or business.

5.6 Building and adapting consultancy/advisory business models

Another change to agricultural advisory/consultancy work was the development of new advisory/consultancy business models, and for many this was something developed over time and with the pace of agriculture technology development. A remote sensing specialist in a farm input supply firm explained how they developed additional services for variable rate fertiliser application:

> *'… So, soil sampling is where we started [with agriculture technology/SFTs] because it was … the obvious way that people wanted to go …we now make our money out of soil sampling, … If you have got a variable rate spreader, you are doing variable rate P and K. What's the next step? Well… they can do variable rate nitrogen based on satellite imagery' (UK, Adviser 17).*

Many of the respondents actively grappling with options and opportunities for their services, which included negotiating new roles, as one person noted:

> *'where does the horticultural adviser fit [if the relationship is between the robot weeder supplier and the farmer]? [They can provide consultancy] Advice on crop spraying spacings maybe? The crop varieties? The type of crops you are growing? Nutritional requirements?… [still] what gives that plant the best opportunity to thrive?' (UK, Adviser 9).*

Another adviser was looking for efficiencies in their service model:

> *'I'd like to get to a point where agronomy advice is not provided solely from field walking, … for example, an agronomist would walk 10 to 15,000 acres a year. I think we could get one agronomist to 100,000 acres if we use the right technology' (UK, Adviser 17).*

A company founder described how they planned to incrementally adapt their business model as they gained expertise to consider strategies for providing services related to robotic harvesting systems:

> *'…we want to put ourselves in the driver's seat here with this 'harvester as a service model' … where [instead of] operating the robots ourselves, … we need to switch this to a model where the farmer operates our robots, and we are a service provider, and provide … maintenance [and] advice, but still taking the robots away when they are done' (UK, Company 2).*

Generalist advisers described changing their business models away from advice per hectare to hourly charges, given the additional time spent in the office analysing data in additional field visits:

> *'…what has changed somewhat is probably how we [agricultural consultants] value ourselves. ….for quite a lot of clients now taking a different approach in terms of the way that we charge them, I charge them for my time' (UK, Adviser 8).*

A number of advisers, associated with SFT companies, spoke about the shift to on-line consultancy services:

> *'We believe in purely online [consultancy service provision]. We do not believe in putting boots on the ground' (Australia, Company 3).*
>
> *'And I'll just log on to this … platform that I'm using, and they [clients] can log on to the same thing. I'm like, you click on that Scout report and look at that picture. And they are like, Ah, okay, I see what you mean… so we can talk through it… that's quite productive' (UK, Adviser 10).*

5.7 Intermediary work

Advisers play important intermediation roles which is a largely neutral and client-centric approach rather than championing any particular SFT. These roles can include playing a facilitating and supporting function with respect to projects (e.g., UK, Adviser 16), helping the farmer integrate SFTs effectively into day-to-day activities, acting as a filter often in the capacity as peer user or tester, as a convenor and source of network knowledge, or as a conduit between farmers and SFT companies.

Advisers described their work in assessing tools being offered to their clients as well as working with technology providers. For one adviser, the expectation of their clients was to bring knowledge of other farmers' experiences with particular tools:

> *'… they [clients/farmers] look for new information. But they kind of rely on me to see what everyone else is doing, what's working, what is not. And suggestions from me on what [tools/technologies] they should be trialing' (Australia, Adviser 2).*
>
> *'…finding out exactly what the reliability of things [tools/technologies] are before advising on them,…. having an idea of [what] … problems might be …and then trying to get your head around it yourself, and between the service provider, so that they can be called upon in those worst-case scenarios…' (Australia, Adviser 6).*

Advisers characterised their role as a filter between tools and their clients:

> *'We're a gatekeeper for a lot of these growers about data and tools as well and about technology' (Australia, Adviser 1).*

Another adviser described their role in facilitating the interest of their clients in use of specific tools, if they saw a clear benefit for them:

> *'I try to find the 10% changes [in farm production from use of tools/technologies]. I try to find the big ones [increases in productivity] and then … if they are [growers/clients] not interested, I'll start making them interested with, say, satellite imagery' (Australia, Adviser 3).*

6 Discussion

We discuss these results with respect to the research question: How is work changing for advisers in the UK and Australia when supporting farmers to implement SFTs?

6.1 Advisory roles in the use of smart farming technologies are evolving

The first main way in which work is changing for advisers working with SFTs is that their roles are evolving. Experienced former field-based advisers in private advisory services, farm consultancy or farm input suppliers/resellers, have adapted their professional practice to specialise in smart farming over their career, and as a result now have different forms of connection with farmers. This contrasts with suggestions that advisers are being replaced by new advisers from SFT companies without agronomic backgrounds (Ingram and Maye, 2020) or being replaced by digital technologies all together (Fielke et al., 2020). Advisers described their roles as having evolved with available technologies, such as variable rate technologies. These evolving roles were bifurcating, being to field or office-based roles, with remote advice provided either direct to farmers or to field staff who then worked directly with the farmer in face-to-face roles and specialising to either focus as a smart farming technology specialist or to considering the fit of SFTs to a whole farm context. While advisory roles in the 'front office' and 'back office' have previously been noted (Laurent and Labarthe, 2013; Eastwood et al., 2019; Rijswijk et al., 2019), our findings suggest that advisers are choosing different paths in their advisory work and this trend of adapting their consultancy services and business models is strengthening, particularly in the cropping/arable agriculture sectors. This is not to say that the replacement of advisers or the lack of agronomic knowledge will not be a problem in the future, particularly as experienced professionals retire, however currently our findings suggest diversification and specialisation in advisory work rather than replacement. We do note however the limitations of our study in that our sample of advisers did not involve advisers that may have lost jobs or work because of the smart farming transitions underway in agriculture.

We found many of the hypothesised roles for farm advisers in smart farming coming to fruition. These included roles in: digital data collection, organisation and interpretation; providing support to farmers in making technology investment choices; defining the value propositions that technology offers (Ayre et al., 2019); and, assisting farmers create value from technology (such as through agronomic and/or whole farm management advice) (Fielke et al., 2020). Further we identified roles of advisers in developing relationships with new partners, like technology companies, and through on-line platforms, thus altering communication patterns of advisers and others in the agriculture innovation system with farmers (Rijswijk et al., 2019). We conceptualise this bifurcation and specialisation in advisory roles and work in Figure 1. This is not to suggest that an advisor operates in one specified role, rather their roles operate across a spectrum whereby their work is evolving and may change in emphasis.

6.2 Expanded knowledge brokering and intermediation roles of advisers in the application of smart farming technologies

The second way in which the work of advisers is changing is that they are playing an expanded role in the agriculture knowledge system as knowledge brokers and intermediaries. We found agricultural consultants who are digi-specialists acting as knowledge brokers (Klerkx et al., 2019), and different advisers, work on different fronts in their knowledge brokering. Digital specialists, commonly based in commercial companies, were involved in knowledge brokering by supporting the learning needs of (field) agronomists or consultants providing advice to clients at a crop or field level. Other advisers, not only digi-specialists, worked on other knowledge brokering fronts involving: scanning for best fit in technologies (for both the advisory business and the farm decision contexts); providing 'help' (as identified by Charatsari et al., 2022, p6) related to the adoption of SFTs, and in supporting farmers in the transition of their farm practice; spending considerable time in understanding different digital technology options to help their clients evaluate the value of a particular digital technology; and interpreting digital data for farmers. These sense making tasks of advisers are essential in 'making Precision agriculture workable' for farmers, as suggested by Higgins et al., (2023, p. 8).

In addition to knowledge brokering, we found wide ranging intermediary work conducted by advisers at several interfaces. Drawing on Kivimaa et al.'s (2019) typology, we identified characteristics of *process intermediary* work, with advisers facilitating and supporting functions in projects and processes contributing to SFT transitions. In doing this advisers develop connections between other advisers and farmers, between farmers and technology companies and, as part of wider innovation networks, interactions with researchers. The work of *user intermediaries* was also identified. These advisers work with user support organisations often in trials of SFTs to help accelerate uptake by farmers of tools and technologies. They draw on their knowledge of farmers and their farming systems. These advisers were also called on to represent users at the interface with SFT developers to communicate user preferences to them. Aligned to Kivimaa et al. (2019) characterisation, we found that advisers in both these intermediary roles rarely have any explicit agency or agenda, but rather their SFT work practices are emergent as they respond to demands for information and support from farmers. We suggest these expanded roles in intermediary work represent a key change for advisers from SFT transitions, and the importance of these roles has not been recognised in the context of the agricultural advisory system to date (Fielke et al., 2020).

While double-mediating roles for advisers have been previously identified (Klerkx, 2020) our findings suggest triple, or quadruple mediating roles are becoming more prevalent. This includes adviser-to-specialist advisers, farmers, technology companies, and in some instances: to value chain actors, or public policy actors. The expansion in the number of relationships relates to different knowledge-flow

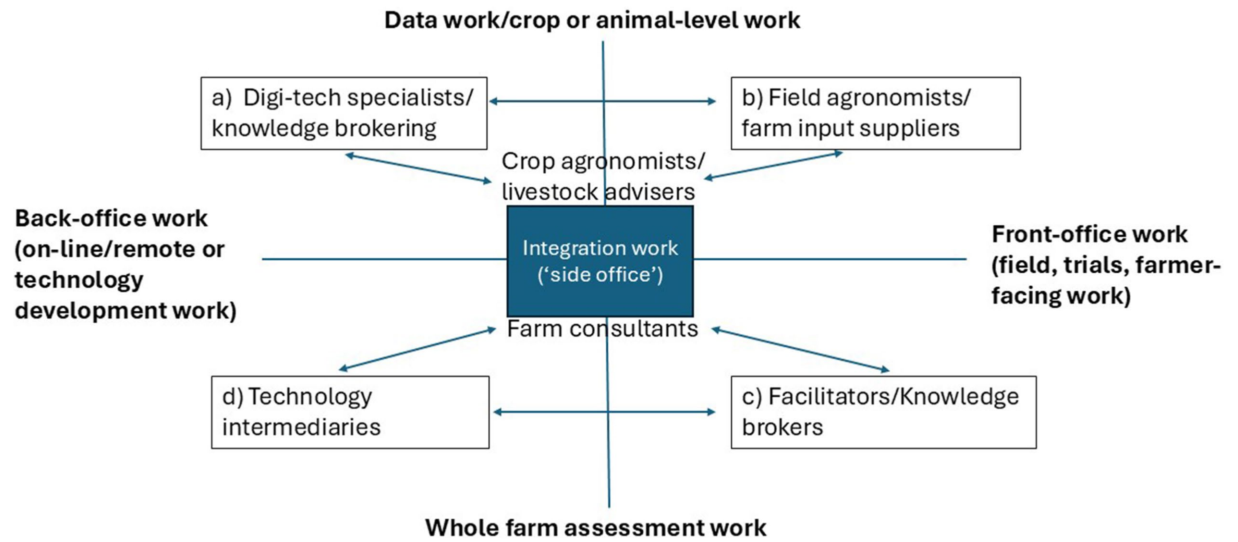

FIGURE 1
Bifurcation in farm advisory work to office or field (horizontal spectrum) or paddock/animal or whole farm (vertical spectrum) and specialisation as a smart farming technologist/specialist (quadrant a-d) or to the whole farm system (quadrant b-c).

fronts which, while offering possibilities for growing or sustaining advisory businesses on one hand, could also create discontinuities in professional lives or identities on the other (Klerkx, 2020; Charatsari et al., 2022). We were not able to precisely discern the weighting to either of these outcomes for advisers except that we found that advisers were looking at ways to curtail the number of technology intermediation roles they took on. Therefore, we suggest that the significance of the work implications of both knowledge brokering and intermediation roles with respect to agricultural advisers' time, capacity and developing new business models requires further investigation.

6.3 The emergence of digiwork in agricultural advising

A third way in which the work of advisers is changing is that advisers were needing to establish practices of integration, or 'digiware' (Ayre et al., 2019) to manage the new representations (i.e., ways of representing farm system dynamics in digital formats), materials (i.e., new digital instruments, equipment and hardware) and social relationships (i.e., as intermediaries and knowledge brokers; outlined in the previous section). These practices, which we term digiwork, are necessary for them to gain benefit from SFTs for their clients and their own businesses. This work involved learning about technologies and applications, building their own software /data analytic platforms, liaising with technology projects and technical specialists. This work also represented risk for advisers and their businesses, particularly when there is often not a clear value proposition for integrating a digital tool or service into their service delivery. We therefore identify integration work as a challenge and risk to advisers, a point also intimated in the integration work of advisers within the context of the agro-ecological transitions (Coquil et al., 2018). We found that the SFT integration work practices of advisers are characterised by two main dimensions: 1) they operate at distinct levels within the smart farming knowledge system; and 2) the increased time commitments (work duration) required and networking capacities for learning and coordination.

The distinct levels within the smart farming knowledge system relate to the integration work of individual advisers, the advisory business and the farming system (Ayre and Nettle, 2015). At each level, there are different sets of symbolic, social and material practices involved (Ayre et al., 2019). At the level of individual advisers for example, advisers were integrating software from different SFT companies and products to build unique and tailored digital platforms or datasets. At the level of the advisory businesses, advisory business owners and their staff were integrating digital data and tools at the interface between what others have identified as the 'front office' (extension activities) and 'back office' (research and development activities) (Laurent and Labarthe, 2013), hence our denotion of the 'side office'. We propose the metaphor of the 'side office' to connote the activities of advisers that include strategic and expert coordination of diverse materials (e.g., digital hardware), symbols (e.g., digital data representations and digital software) and social entities (e.g., people, organisations including technology developers, digital specialists and farmers. Here advisers perform integration practices of edge) (Koutsouris, 2014) and boundary spanning (Klerkx and Proctor, 2013), which are practices critical to 'social integration' dynamics in agricultural innovation (Stræte et al., 2023). We propose 'side-office' activities to be unique integration practices of advisers in smart farming and digital agriculture contexts. Side-office work also includes practices of mutual learning (through co-inquiry and collaboration) (Blackmore et al., 2018), as advisers and farmers together address the challenges of integrating new information of farm performance from digital tools and services into farm management decisions. This complements and extends the metaphors that have been used to describe complex dynamics in pluralistic extension and advisory

10.3389/fsufs.2025.1542007

TABLE 4 Examples of digiwork—the advisory practices of integration in smart farming contexts.

Advisory practices of integration (the 'side office') in smart farming	Examples from this study
Social practices	- Communicating and interacting with different actors (clients, advisers, technology developers etc.) and organisations - Sensemaking with clients to assess the capacity of digital tools and technologies farmers had invested in and to understand how digital information can support farm decision making
Material practices	- Coordinating software, hardware, digital tools and equipment - Dealing with a lack of interoperability between platforms
Symbolic practices	- Generating, curating, interpreting and representing digital data in various formats

systems whereby 'extension' activities and 'research and development' capabilities are both important in providing support to farmers (Eastwood et al., 2017).

At all levels these new work practices had to be integrated with the more traditional advisory duties, as identified in the study of Charatsari, et al., (2022, p. 350). While the term 'digi-grasping' has been coined to describe how an adviser develops practices and knowledge in digital agriculture (Rijswijk et al., 2019; Fielke et al., 2021) we suggest 'digiwork' better represents the 'doing' of integration and the distinct dimensions of evolving advisory work. The digiwork of agricultural advisers involves routines and understandings that emerge from the relations between digital technologies and tools, people and groups (i.e., technology developers and their services, farmers, other advisers) and the sites and places in which they work and interact. The value for clients of digiwork is in the quality of the integration practices performed by advisers as they translate, coordinate and assemble different meanings and effects (Higgins et al., 2023; Sutherland and Calo, 2020), and, importantly, in how a value proposition for smart farming is formed (Ayre et al., 2019; Klerkx, 2021). We propose the concept of digiwork, as constituted by the key practices highlighted in this study (Table 4) as an important contribution to understanding the evolving advisory context in addition to that of professional identity (Charatsari et al., 2022) and competencies (Ingram and Maye, 2020).

Further, the required time commitments (work duration) and networking capacities for learning and coordination is an important and underrepresented aspect to advisory work in the smart farming transition. The practices of integration (above) are interconnected with work duration and the advisers' motivation to increase their own value to their clients. Developing new roles, working out new business models and learning new software programs takes time and such investment is a signal of commitment to the transition for their clients, however the work of developing business models, introduces risk. There were a range of adaptations being made, including from small changes (e.g., charging for the time spent) through to more substantial changes (e.g., developing and delivering add-on services or service packages or trialing contract services or licensing fees), and these new advisory business models are recognised as an important indicator for how digital agriculture is unfolding (Fielke et al., 2020; Birner et al., 2021). However, these changes and the integration work of advisers, has occurred mostly spontaneously, with the work duration burden resting almost entirely with the advisers and their businesses and with minimal support or coordination from formal institutions or programs. In the UK, the facilitation and intermediary roles were supported with dedicated government funding, which were less prevalent in Australia. Formal learning systems, such as through education and training programs, which would potentially reduce work duration for advisers, was largely ad-hoc or in-house, through the technology companies. While smart farming technology companies may embed farm advisory services in their offerings, such a technology-led, commercialised advisory service will not necessarily provide the capabilities for digiwork, nor support the level of ambition of the agriculture 4.0 transition, which requires strong public-private partnerships (Eastwood et al., 2017).

Table 5 summarises the key challenges that need to be addressed to improve the work situation of farm advisers in the era of Agriculture 4.0, and proposals to overcome them.

7 Conclusion

In this paper we have considered the implications of changes to advisory work in the context of the challenges and opportunities of the Agriculture 4.0 transition. We show that the work practices of advisers in supporting the implementation of SFTs represent a particular function and role for advisers, being that of knowledge integration. We suggest this is an important contribution to understanding the evolving advisory context in Agriculture 4.0, extending the work to date related to professional identities and competencies of agricultural advisers. Theorisation of advisory work as 'digiwork', or the symbolic, social and material practices of knowledge integration, and the metaphor of the side office, addresses a gap in current understanding of the advisory system with respect to SFTs. Our study also integrates and advances scholarship concerning work assessment frameworks, advisers' roles and professional competencies, and their skills and intermediation practices. We also raise the issue of the current response of advisers to Agriculture 4.0 challenges, which reflects the privatised 'laissez faire' approach of advisory systems of both Australia and the UK and the fragmented nature of support for SFT in these pluralistic settings. It raises questions about where the responsibility for responding to the many new demands on advisers' work lies. Building capacities and capabilities suited to the range of integration work needs is important, recognising that this requires social as well as software and analytical skills, and some balance of self-directed learning and formal training.

TABLE 5 Summary of challenges for advisory work and proposals for addressing the situation.

Challenges	Proposals to address the work situation
Bifurcation and specialisation of advisory roles fragments the advisory system.	Government or industry investment to improve coordination and enhance networking in the advisory system and address farmer needs.
Work duration in developing knowledge, learning and networking is a direct cost to independent advisers/small advisory businesses.	Subsidisation of adviser involvement in new technology developments and with pre-commercial start-up companies working with farmers.
Developing new business models, introduces more financial risk for independent advisers/small advisory businesses.	Formation of an advisory network for agriculture 4.0 learning, and incentives for involvement. Direct subsidisation of formal education/short course involvement of farm advisers.
Expanded knowledge brokering and process intermediation (e.g., triple or quadruple intermediation work) is time consuming and increases workload, with upper limits to the number of relationships to coordinate and maintain.	Investment in knowledge brokering, user and process intermediation by government or industry.
Integration work (digiwork) and side office activities are less visible to technology developers, government and industry. The work is unaccounted for in advisory fee-for-service structures (i.e., limited ability of advisers to charge for this work)	Collective assessment of the learning needs and educational demands related to these roles to develop and deliver targeted capability development. Cross-industry knowledge sharing and support for development of business models that accounts for integration work. Public and private funds to facilitate pre-competitive development of platforms to improve inter-operability between platforms

To support the integration and management of SFTs, digital management systems are required that enable communication amongst the farm management team (e.g., farm managers, farm workers, contractors, consultants, and smart farming specialists who may be engaged to manage and analyse data). Without such systems, the relevance and meaning of data to support on-farm decision making is not fully realised or can be compromised. Finding effective and efficient ways to engage advisers in the development of new tools and services would improve their integration with the farm management context and help realise benefits and reduce risks from investment on-farm and in their application to realise the value and benefits from engaging in smart farming. Fostering precompetitive development of platforms with public and private funds to allow more interoperability between platforms would save time and reduce risk for advisers, and lessen the integration work and responsibility that advisers have taken on as part of their digiwork.

Our findings suggest that government, technology companies and the agricultural sectors need to consider the inter-relationships between the different dimensions of advisory work in smart farming and the consequences of not supporting the farm advisory system in the Agriculture 4.0 context. In a rapidly evolving environment, including from the technological side, such as machine learning applications in advisory services and from the changing demands and needs of farmers, stronger and more cohesive strategies to support learning and communication are required. Given the critical role advisers play in facilitating on-farm change and the uncertainty regarding new roles and disruption to the advisory system there are important roles for government in acknowledging and supporting the digiwork and progress ways to avoid technology-centered education and advisory systems.

We note some limitations in our study being the self-selection process of advisers which has limited the range of potential advisory experiences canvassed, such as those advisers who may have lost jobs or work because of emerging technologies replacing advisory tasks such as Artificial Intelligence applications. Younger, less experienced advisers and advisers directly involved in selling agricultural technologies were also underrepresented in our study. We did not examine or compare changes to salaries, benefits or career progression among the advisers, and this is an important area for future research related to advisory work.

We recommend future research into the significance of the work implications of both knowledge brokering and intermediation roles with respect to agricultural advisers' time, capacity and developing new business models. Further research is also recommended into the governance of advisory systems in the context of smart farming, including who takes on the responsibility (and burden of work) for building advisory capacities/capabilities, particularly the differences in, or improvements in, support that may emerge in different countries. Furthermore, research is needed to better understand the specific learning needs and educational demands of advisers and investigate flexible, vocational and educational pathways for professional development in digiwork. While our study did not focus on the replacement of advisers, such as with machine learning systems, the emergence of new knowledge systems is a critical domain for understanding changes to work and where more research is warranted.

Data availability statement

The datasets presented in this article are not readily available because research participants have not provided consent for raw, anonymized data to be shared. Requests to access the datasets should be directed to ranettle@unimelb.edu.au.

Ethics statement

The studies involving humans were approved by Human ethics advisory committee (HEAG), University of Melbourne. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

RN: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing. JI: Conceptualization, Formal analysis, Investigation, Methodology, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing. MA: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Validation, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. RN financial support from the OECD Sustainable Agriculture Fellowship program to conduct research in the UK. MA financial support and links to professional networks from Crop Consultants Australia to conduct the research with Australian advisors.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Gen AI was used in the creation of this manuscript.

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Appendix

*Link to public call for advisers to participate in the research.
https://docs.google.com/forms/d/e/1FAIpQLSfH8hdR5BzO44QYFwIywT2i9qyURZv1Dg5OHueZkivHHtXHuA/viewform

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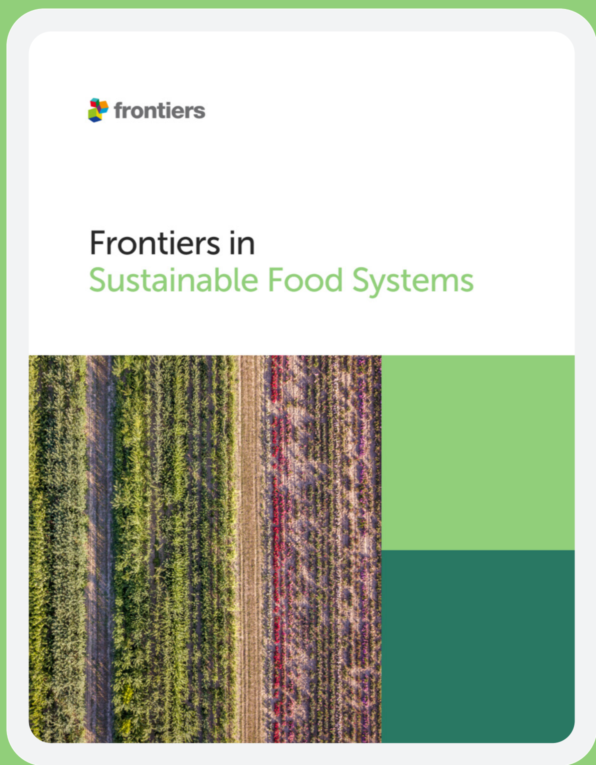

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