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RESEARCH ARTICLE

Combining social, ecological and economic approaches in knowledge co-production enables the identification of sustainable farming options

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Abstract

1. Farming systems face an increasing sustainability challenge requiring integrated solutions to minimize the trade-offs between the social, ecological and economic dimensions of sustainability. Yet, most research remains siloed, limiting interdisciplinary understanding of farming systems as coupled social-ecological systems (SESs) and precluding holistic solutions. Addressing this gap, we employed an interdisciplinary knowledge co-production approach in Kilimanjaro, integrating social, ecological and economic data to understand the multidimensionality of the farming systems.
2. We first surveyed 306 farmers and used multivariate analysis to categorize the farming systems. Based on data from semi-structured interviews with 15 farmers and field observations of agricultural plots they own or manage, we conducted a cost–benefit analysis of each farming system. Through thematic analysis, we revealed the perceived impacts of farming practices on biodiversity, soil and yields. We triangulated these findings with those from ecological studies conducted on the same agricultural plots. We finally identified challenges to and solutions for sustainable farming, complemented by five key informant interviews.
3. We found a heterogeneous agricultural landscape characterized by maize-bean, homegarden and coffee farming systems. All systems were estimated to be profitable but sensitive to environmental and market-related shocks. Farmers and key informants identified four major challenges, largely similar across farming

systems: biophysical constraints, production costs and market constraints, infrastructure limitations and gaps in agricultural extension support.
4. Proposed solutions included farm-level interventions such as manuring, biological pest control and planting drought-resistant crops, which were low-cost practices and perceived to offer multiple benefits. Notably, using high-cost agrochemicals, particularly in the maize-bean system, was perceived to have long-term negative environmental impacts. These perceptions were consistent with the findings from the ecological studies. Institutional-level solutions involved leveraging cooperatives and improving agricultural information, while policy and government-level solutions focused on subsidies, incentives for organic produce, market regulation and tax reductions.
5. By integrating social, ecological and economic dimensions in an interdisciplinary knowledge co-production approach, we identified context-specific challenges and actionable solutions that account for local practices and structural support needs. This approach, which values farmers' experiential knowledge alongside ecological and economic insights, has the potential for wider utility in guiding sustainability in farming systems beyond Kilimanjaro.

KEYWORDS
agroforestry, farming systems, knowledge co-production, mixed-methods, smallholders, social-ecological systems, sustainable farming

1 | INTRODUCTION

Farming systems play a vital role in supporting the livelihoods of about 40% of the global population, yet maintaining their long-term sustainability has become increasingly challenging (FAO, 2015, 2019, 2021; Garibaldi et al., 2017; Hodbod et al., 2016). Declining soil fertility, unreliable rainfall and market fluctuations, among many other problems, continue to threaten the productivity and income stability of mainly smallholder farmers (FAO, 2015, 2019, 2021). At the same time, efforts to increase production often degrade land and water resources, resulting in myriad impacts, including biodiversity loss and trade-offs between short-term gains and long-term sustainability (Cuni-Sanchez et al., 2019; FAO, 2015, 2019). Understanding how social, ecological and economic factors interact within farming systems is therefore critical for identifying realistic pathways towards sustainability. The sustainability of farming systems here is understood as '*practices that do not have adverse effects on environmental goods and services, are accessible to and effective for farmers, and lead to improvements in food productivity*' (Pretty, 2008). Achieving such sustainability in practice requires several considerations. First, it calls for integration of social, ecological and economic dimensions through interdisciplinary approaches that draw on both the social sciences (including economics) and the natural sciences (Fischer et al., 2025). Second, it involves recognizing farming systems as coupled social-ecological systems (SESs) (Giller et al., 2015, 2021; Pretty, 2008, 2018; Tittonell & Giller, 2013) to avoid simplistic solutions (Bakker et al., 2005). Third, it requires linking farm-level decisions and practices shaped by biophysical conditions, knowledge (both experiential and experimental) and livelihood needs with environmental and economic outcomes (Berkes et al., 2000; Ewert et al., 2023; Rasmussen et al., 2018). This calls for research approaches that transcend monodisciplinary silos and knowledge co-production that reflects the multidimensional nature of real-world farming systems (FAO, 2021; Fischer et al., 2025).

The need to integrate knowledge from a range of sources corresponds to a broader movement in sustainability science towards integrating disciplinary scientific knowledge with experiential knowledge of actors in knowledge co-production (Norström et al., 2020). In the context of farming systems, this is reflected in the need to combine farmers' experiential knowledge with empirical scientific observations and expert knowledge. For example, to address the disconnect between generalized 'best practices' and context-specific farm realities (Cook et al., 2021). This includes farmers' practical understanding of local soils, crops and risks, alongside ecological and economic analyses that capture biophysical processes and material constraints, but also their local ecological knowledge, which can complement scientific ecological evidence (Pretty, 2008). Sustainability research emphasizes that farmers' knowledge is not merely contextual background but constitutes a critical source of insight into how environmental change, management practices and livelihood strategies interact (Berkes et al., 2000; Norström et al., 2020). When combined with ecological evidence and economic assessment, such knowledge can reveal feedbacks, trade-offs and constraints that are often missed by single-discipline approaches. This is particularly relevant in smallholder systems, where decisions are shaped simultaneously by many factors, including environmental variability and market conditions. Such knowledge integration is not only analytical but also action-oriented and helps form locally grounded solutions, a central theme of the knowledge co-production literature (Norström et al., 2020; Tengö et al., 2014).

Despite the potential for interdisciplinary knowledge co-production, most studies of farming systems employ a monodisciplinary approach (Garibaldi et al., 2017; Hodbod et al., 2016; Li et al., 2021). These cannot offer a comprehensive understanding of farming systems as socio-ecological systems, nor solutions that acknowledge the multidimensionality of the sustainability challenge. For example, studies employing natural science approaches offer valuable insights into the effect of land use change, intensification or technology adoption on ecosystems (Altieri & Nicholls, 2003), but often overlook the social dimensions that shape farmers' perspectives on and decisions to engage in certain management practices (Tscharntke et al., 2012). While interdisciplinary studies of agricultural sustainability are not uncommon (Accatino et al., 2022; Watson et al., 2024), few explicitly integrate social, ecological and economic dimensions within a single farming system (Fischer et al., 2025; Pretty, 2018) or integrate experiential and scientific knowledge to co-produce actionable knowledge that promotes place-based sustainability (Šūmane et al., 2018).

This lack of integration is reflected in current recommendations for sustainable farming, which often adhere to disciplinary boundaries and knowledge sources. Those emerging from natural sciences are focused on the adoption of climate-smart agricultural practices, such as soil conservation, crop diversification (Delvaux et al., 2020; Ogisi & Begho, 2023) and the use of organic inputs, including manure application and crop residue management (Branca et al., 2022; Sileshi et al., 2025). Meanwhile, social sciences and economics focus on recommendations such as improved smallholder access to credit and markets, agricultural extension support and farmer education (Branca et al., 2022; Delvaux et al., 2020; FAO, 2019), as well as on strengthening rural infrastructure and farmer organizations (Delvaux et al., 2020; FAO, 2019). To be sustainable, these recommendations must be conceived and applied in an integrated way and tailored to the specific conditions of farming systems and the social-ecological contexts in which they are embedded (Wreford et al., 2017). Achieving this requires an understanding of how farming systems are structured in specific social-ecological contexts, that is, characterizing farm types, land use patterns and livelihood strategies, without which it is challenging to design locally relevant solutions (Fischer et al., 2025; Wreford et al., 2017).

In view of the above, this study adopts an interdisciplinary knowledge co-production approach to examine farming systems on the southern slopes of Mount Kilimanjaro (hereafter Kilimanjaro), where agriculture is the region's main economic activity, supporting the livelihoods of about 2 million people (National Bureau of Statistics, 2023; Soini, 2005b). Specifically, we aim to: (1) characterize farming systems in Kilimanjaro, and (2) identify the relevant challenges to, but also solutions for, farming systems' sustainability in Kilimanjaro. We combined qualitative and quantitative data obtained through a survey, semi-structured interviews, field observations of agricultural plots, a systematic literature review of ecological studies conducted on these agricultural plots, and key informant interviews to achieve these objectives. This approach offers a comprehensive view of farming systems as dynamic, multidimensional SESs shaped by multiple challenges that need co-produced, locally grounded and actionable solutions to foster sustainability.

2 | METHODS

2.1 | Study area

We conducted our study in Kilimanjaro, Tanzania (Figure 1), renowned for its diverse ecosystem types spanning an elevational gradient from 700 to 5985 m.a.s.l., focusing on the area below 1800 m.a.s.l. outside the Kilimanjaro National Park. Kilimanjaro has two distinct wet seasons: long rains (March–May) and short rains (October–December). Mean annual rainfall is c.800 mm below 1800 m.a.s.l. and peaks at 2100–2700 mm at 2200 m.a.s.l. (Hemp, 2006). The fertile volcanic soils and a suitable climate in the area have been conducive for agriculture over the past 200 years (O'kting'ati & Kessy, 1991). Agriculture is largely small-scale and subsistence-oriented; yet it also provides cash income through crop and livestock sales (Mdoe & Wiggins, 1997; Soini, 2005b). Agriculture in Kilimanjaro has undergone notable transformations between the mid-1960s and 1980s. Initially, the lowlands (700–1000 m.a.s.l) were dominated by intensive maize and beans cultivation, while mid- (1000–1200 m.a.s.l) and highlands (1200–1800 m.a.s.l) were mainly maintained as homegardens (Ikegami, 1994; O'kting'ati & Kessy, 1991). In the late 1980s, increasing population, changing climatic conditions, land use patterns and shifting markets resulted in changes to the elevational distribution of crop types as highlighted in Sections 4.2.1–4.2.3 (Ichinose et al., 2020; O'kting'ati & Kessy, 1991; Soini, 2005b). Similarly, forest loss has been substantial, with approximately 13,000 ha converted to agriculture between 1976 and 2000 (Grossmann, 2008). Future projections for 2030 anticipate a 57% reduction in grasslands and a 6% decrease in forests, primarily due to conversion to agricultural and urban land uses (Said et al., 2021).

Previous research in Kilimanjaro has shown that land-use and climate changes greatly affect biodiversity and ecosystem functions in the area (Agrawala et al., 2003; Said et al., 2019). Some ecological research studies conducted within the KiLi project (Hemp et al., 2018), on 65 study plots (50 m × 50 m, with five replicate plots within each ecosystem) spanning 12 ecosystem types established since 2010 (further details in Hemp et al., 2018), reached similar conclusions (Classen et al., 2015; Peters et al., 2019). Notably, these studies show that conversion of natural habitats to

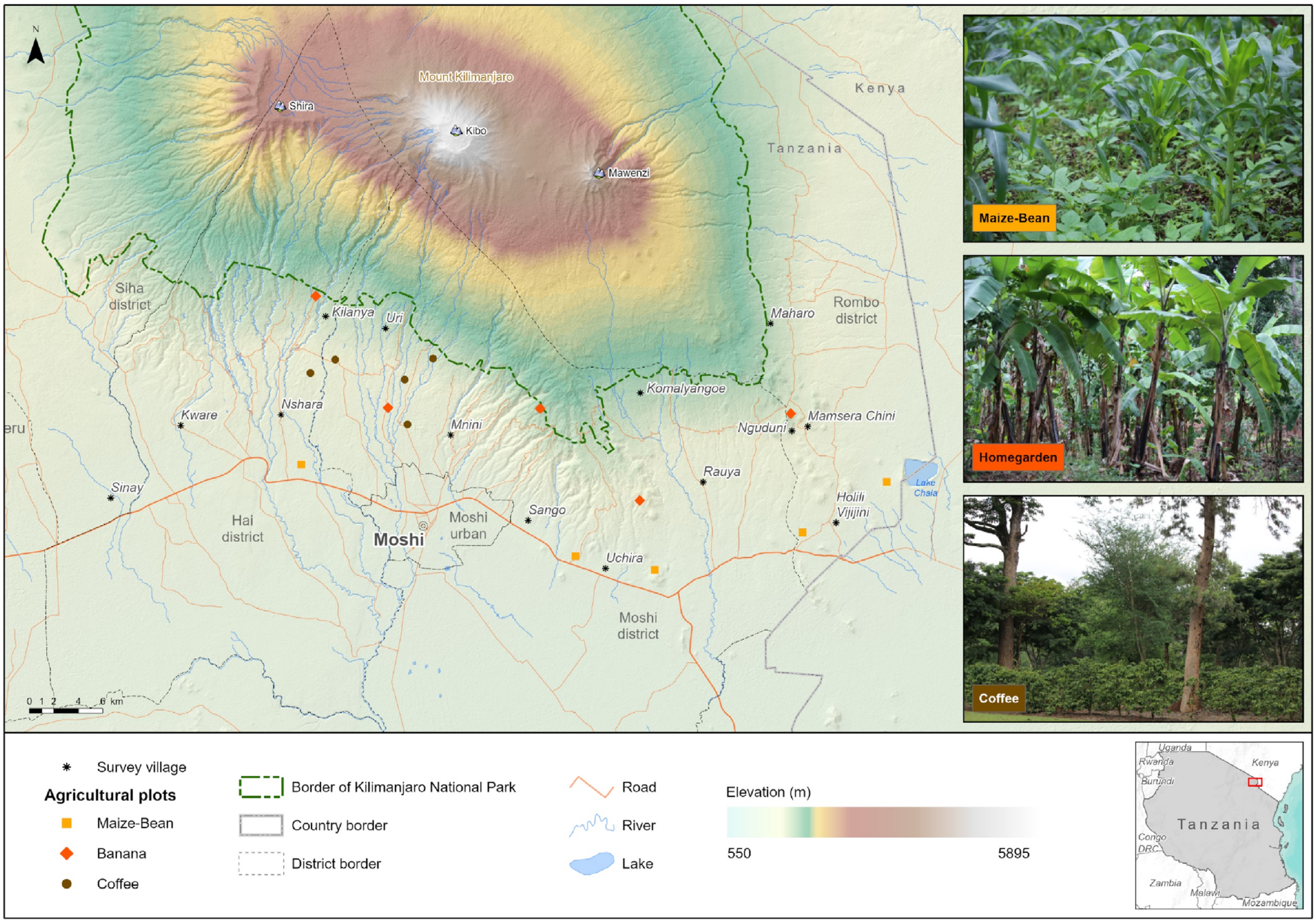

FIGURE 1 Map of the southern slopes of Kilimanjaro showing the 14 villages where we conducted a questionnaire-based survey with 306 farmers and the 15 agricultural plots whose owners or managers we interviewed, as well as where field observations were performed.

agriculture reduces soil carbon, alters nutrient cycling and lowers species abundance and diversity. However, agroforestry systems, including homegardens managed by smallholder farmers, maintain higher biodiversity and provide benefits such as pollination and pest control (Hemp et al., 2018). These findings demonstrate that biodiversity supports nature's benefits and that land-use impacts are shaped by climate and management practices. Altogether, the past and future changes depict intertwined social, ecological and economic dynamics that provide the context within which farming systems in Kilimanjaro continue to evolve, while also raising concerns about their sustainability.

2.2 | Study design and data collection

Between March and November 2022, we collected qualitative and quantitative data using an interdisciplinary empirical approach (Table 1). To provide a basis for characterizing farming systems, we conducted a questionnaire-based survey of 306 smallholder farmers in 14 villages, selected by stratified random sampling from 224 villages in the study region; see Table S1 for details. Due to variations in climate, vegetation and land use (Peters et al., 2019), and potential differences in social characteristics (Misana et al., 2012), we selected villages along both longitudinal, that is, eastern (Rombo), central (Moshi Rural) and western (Siha and Hai) and elevational gradients, that is, lowland (700–1000 m.a.s.l), midland (1000–1200 m.a.s.l) and highland (1200–1800 m.a.s.l) (Gross et al., 2025; Sanya et al., 2025) to capture the full range of biophysical and social characteristics across Kilimanjaro. We employed random sampling of geographic coordinates to select households within villages. We only surveyed people over 18 years old. We collected data on the priority crops, location, farming practices, estimated farmed area for each crop and socio-demographics, as detailed in Supporting Information S1. We piloted the questionnaire-based survey (hereafter, farmer survey) during iterative rounds of training field assistants, who served as respondents during the questionnaire pre-testing (more details in Sanya et al., 2025).

Next, we conducted semi-structured interviews with 15 smallholder farmers and farm managers of large-scale coffee plantations (collectively referred to as farmers) who owned or managed agricultural plots of the KiLi project (Hemp et al., 2018). The farmers' interview guidelines (Supporting Information S2) were piloted with

TABLE 1 Overview of the research design, for which we applied mixed methods sequentially, i.e., insights gained from the farmer survey (research objective 1) informed data gathering to achieve research objective 2.

	Interdisciplinary methods approach			
Research objective	**Method**	**Data type**	**Data analysis**	**Information gathered**
1. Characterize farming systems in the Kilimanjaro	Questionnaire-based survey with 306 smallholder farmers across the study region	Quantitative socio-economic data	– Multiple Correspondence Analysis – Agglomerative Hierarchical Clustering	– Priority crops – Predominant farming practices – Underlying socio-economic characteristics – Identification of main farming systems
	Semi-structured interviews with five farmers of each of the three farming systems	Quantitative economic (costs, yield) data	Cost-benefit analysis	Costs and benefits of each farming system
2. Identify relevant challenges to, but also solutions for, farming systems sustainability in Kilimanjaro		Qualitative social data	Descriptive analysis	Perceived impacts of farming practices on biodiversity, soil conditions, and yield
			Thematic analysis	Challenges to, and solutions for sustainable farming
	Field observations of these farming systems	Qualitative ecological (plot characteristics) data		General characteristics of the farms and practices. Topographical features (e.g., slope, contours), types of crops grown, signs of pests or diseases)
	Systematic literature review of ecological studies conducted on these farming systems	Qualitative ecological (biodiversity, ecosystem functions) data		Land use impact on biodiversity, soil conditions, and yield
	Interviews with five key informants	Qualitative social data		Challenges to, and solutions for sustainable farming

nine farmers across four villages where we conducted the farmer survey. The farmers interviewed represented three farming system categories that were based on the most prioritized crop types from the farmer survey. These included: maize fields, often intercropped with beans ($n=5$ smallholders), homegardens dominated by banana ($n=5$ smallholders) and coffee plantations ($n=5$ farm managers). The latter were considered, given the commercial importance of coffee in Kilimanjaro. Coffee cultivation is concentrated in plantations owned by cooperatives leased to private investors. We asked the farmers to report on farming practices, plot characteristics and input costs incurred in managing the agricultural plots. Detailed information on input costs (material and labour) focused solely on the previous agricultural season (March–May 2022), which was a typical farming season in Kilimanjaro. If deemed useful, we asked follow-up questions to help farmers recall estimates and provide the necessary information. Recall of recent and routinely managed activities in smallholder contexts is generally reliable in the absence of formal records (Beegle et al., 2012).

Further, we collected yield data for maize, beans, banana and coffee from the 15 agricultural plots. Yield data were based on empirical measurements done between March 2022 and September 2023 from nine 5×5 m subplots within the plots. Maize and bean yields were assessed using standard agronomic measurements, including cob/pod counts and grain weights, recorded during harvest. Banana yield data were collected through repeated visits (over 40 per plot) during the harvest period, with bunch weight recorded directly in the field. For coffee, yield estimates were based on measurements of coffee berries from randomly selected trees. For all crops, yield was aggregated from subplot to plot level and standardized to tons per hectare (t/ha). For maize and beans, we used indicative prices from the Ministry of Agriculture (www.kilimo.go.tz) in September 2023. For bananas and coffee, we used the average of farmers' reported prices (see Supporting Information S3 for more details).

We also gathered data on farmers' understanding of the perceived impacts of their farming practices on biodiversity (e.g. pollinators and soil microbes), soil conditions (e.g. soil fertility and moisture) and yield. Finally, we asked open-ended questions to reveal challenges and solutions for enhancing sustainability in farming systems targeting social, ecological and economic dimensions.

Subsequently, we conducted field observations of the agricultural plots to gather information on general characteristics, such as slope and contours, as well as discernible features of farming practices, including the presence of mulch, trees and furrows (see Supporting Information S4). These observations were crucial for validating farmers' responses to interview questions by confirming aspects of farming practices directly observable in the field.

We triangulated farmers' perceived impacts of their farming practices with ecological findings from a systematic literature review. The literature review focused on studies examining the impact of land use on biodiversity and ecosystem functions in the same agricultural plots owned or managed by the farmers we interviewed. The review followed the guidelines by Haddaway et al. (2015) (details in Supporting Information S5).

Lastly, we interviewed key informants with comprehensive local knowledge—four government officials at the district and regional level and a representative of the Agriculture Marketing Cooperative Societies (AMCOS). The questions focused on challenges facing the farming systems and potential solutions to them. The key informant interview guidelines (Supporting Information S6) were not piloted because the questions were specifically tailored to the expertise and institutional roles of the informant.

2.3 | Ethical consideration

We secured research permits from the Tanzania Commission for Science and Technology (COSTECH, reference number: 2022-536-2021-09) and the Tanzania Wildlife Research Institute (TAWIRI) for all work, including interviews, which also adhered to the ethical guidelines of the Norwegian National Committee for Research Ethics in the Social Sciences and the Humanities and the standards recommended by the German Data Forum (2017). For the farmer survey, we obtained ethical clearance from the Ethics Committee of Leuphana University of Lüneburg (reference number: EB-Antrag_202206-11-Martin-Lopez_KiLiSES 02). All respondents provided written and oral informed consent.

3 | DATA ANALYSIS

3.1 | Multivariate statistics to categorize and characterize farming systems

To categorize and characterize the farming systems (RQ 1) based on the farmer survey ($n=306$), we used Multiple Correspondence Analysis (MCA). Active variables included prioritized crop types and predominant farming practices, with the percentage of farm area dedicated to crops serving as a quantitative supplementary variable. We applied Ward's criteria for Agglomerative Hierarchical Clustering (AHC) to produce clusters with minimum within-cluster variance and Euclidean distance as a dissimilarity measure (Ward, 1963). We then generated clusters and tested for significant differences between the first four axes across clusters using ANOVA followed by the Bonferroni test (Table S2). We examined significant differences between clusters based on socio-demographic and other variables related to livestock ownership, income from agricultural activities and collective action (Table S2). We used a Chi-square test for categorical variables and a non-parametric Kruskal–Wallis test for continuous data, followed by Dunn's pairwise comparison test (Table S3). We performed the analysis using XLSTAT software Version 2020.3.1 (Addinsoft, 2020).

3.2 | Cost–benefit analysis

Using the farmer interview data, we performed a cost–benefit analysis of the farming systems. This focused only on the major crops of each system (maize-beans, banana, coffee) using the equations below (Green et al., 2018). Individual costs for maize and bean crops were combined to get farming system-level values.

For each farming system, we calculated gross margin, a standard agronomic measure of farm profitability that accounts for both input and labour costs relative to the revenue obtained from crop sales (Bonke et al., 2021; Penot et al., 2021). Total production costs (Equation 1) included all costs associated with inputs (e.g. seeds, fertilizers, pesticides) and labour. Total revenue (Equation 2) was estimated as the product of market price per unit and yield per hectare. Net revenue (Equation 3) represents the profit remaining after subtracting total production costs from total revenue. Finally, the gross margin (Equation 4) was calculated as a proportion of net revenue to total revenue.

$$\text{Total production cost}\left(\$\,\text{ha}^{-1}\right) = \sum_{m}^{i} \text{Input}_{im}\left(\$\,\text{ha}^{-1}\right) + \sum_{j}^{i} \text{Labour}_{ij}\left(\$\,\text{ha}^{-1}\right) \tag{1}$$

$$\text{Total revenue}\left(\$\,\text{ha}^{-1}\right) = \text{Market unit value}\,(\$) \times \text{Yield}\left(\text{t ha}^{-1}\right) \tag{2}$$

$$\text{Net revenue}\left(\$\,\text{ha}^{-1}\right) = \text{Total revenue}\left(\$\,\text{ha}^{-1}\right) - \text{Total production cost}\left(\$\,\text{ha}^{-1}\right) \tag{3}$$

$$\text{Gross margin} = \text{Net revenue}\left(\$\,\text{ha}^{-1}\right) / \text{Total revenue}\left(\$\,\text{ha}^{-1}\right) \tag{4}$$

We tested the sensitivity of the gross margin of each farming system to changes in input costs, market prices and yields, using scenarios reflecting the magnitude of past fluctuations and trends. The first scenario, *harvest failure*, reflected an 80% reduction in crop yield due to drought, pests or diseases (Kinuthia & UNU-WIDER, 2020; Oerke, 2006), and a corresponding 50% increase in market prices resulting from scarcity. The second scenario, *sustainable intensification*, reflected a 100% increase in material costs due to the higher cost of organic fertilizers and biocides, and a 50% increase in labour costs to account for manual weeding instead of herbicide use. This scenario assumed a 50% increase in yield (Jain et al., 2020). The third scenario, *sustainable intensification with shocks*, reflected the combined effects of increased input costs with the worst-case situation of a 50% decrease in yield and market prices. See Supporting Information S3 for details of the cost–benefit and sensitivity analysis.

3.2.1 | Perceived impact of farming practices

We identified and categorized the perceived impacts of different farming practices mentioned by farmers on a positive-to-negative gradient scale. We triangulated this information with ecological study findings from the agricultural plots (Table S4), encompassing measurements of soil fertility indicators (e.g. soil carbon, nitrogen, microbial biomass and turnover rates; Becker & Kuzyakov, 2018; Gerschlauer et al., 2019; Pabst et al., 2013), biodiversity attributes (e.g. insect abundance and pollinators diversity; Classen et al., 2015; Helbig-Bonitz et al., 2015; Renner et al., 2022; Vogeler et al., 2022) and ecosystem properties (e.g. tree regeneration potential and carbon biomass; Ensslin et al., 2015; Gebert et al., 2020; Njovu et al., 2021; Röder et al., 2017). This triangulation allowed us to assess whether the perceived impacts converge with findings from ecological studies on the same agricultural plots on which the semi-structured farmer interviews are based.

3.3 | Thematic analysis of challenges and solutions to sustainability in farming systems

We employed thematic interpretation of open-ended questions from the farmer and key informant interviews. We identified challenges and solutions for sustainability in farming systems, including those related to farming practices or policy changes within each system. We used MAXQDA 2022 (VERBI Software, 2021) to inductively code emerging themes, following an iterative process where initial familiarity with the data leads to code generation and theme identification, as described by Braun and Clarke (2006). Generated themes are presented in Table S5, along with exemplary quotes that support the research participants' perspectives. Quotes have been anonymised using research participants' codes and randomly assigned two-digit numbers, for example, MBR16 = Maize-beans farmer respondent, CFR10 = Coffee farm manager respondent and GOR04 = Government official respondent.

4 | RESULTS

4.1 | Clusters of farming systems based on the farmer survey

Farmers prioritized maize (88%) and beans (52%), followed by bananas (47%). Other crops, including sunflower, avocados, vegetables, groundnuts, mug beans and cassava, were prioritized by around 30% of farmers, while coffee was prioritized by 9%. More than 90% of farmers practiced rainfed agriculture, while <10% had irrigation systems (Figure S1). For a summary of the respondents' profiles, see Table S6.

The first four axes (F1–4) of the MCA explained 72.53% of the total inertia, capturing the main patterns of crop types and associated farming practices (Table S7). The F1 axis explained 47.5% of the variance and distinguished between farmers applying manure, pesticides and irrigation in coffee farming and farmers applying inorganic fertilizer, pesticides and irrigation for beans (Figure 2a). The F2 axis, explaining 10% of the variance, distinguished between farmers using inorganic fertilizer, pesticides and irrigation in coffee and those applying manure and pesticides to beans and manure to maize (Figure 2a).

The AHC of the MCA results showed four distinct farming system clusters (Figure 2b,c): banana, maize-bean, other crops-maize and coffee. While prioritized crops defined clusters, most farmers cultivated multiple crops. The co-occurrence analysis (Table S8) confirmed this non-exclusivity: for example, 52.6% of maize farmers also grew beans, 23.5% grew bananas, 20.9% grew other crops and 2.3% grew coffee.

The clusters differed significantly along the first four axes, as confirmed by one-way ANOVA followed by Bonferroni post hoc tests (all $p < 0.0001$; Tables S2 and S3). The first, 'banana farmer cluster' ($n = 84$), was dominated by farmers cultivating bananas and using manure in the centre-midland (1000–1200 m.a.s.l) ($\chi^2 = 43.62$; df = 6; $p < 0.0001$). The second, 'maize-bean farmer cluster' ($n = 144$), was characterized by maize–bean farmers across elevation who used inorganic fertilizer. The third, 'other crops-maize farmer cluster' ($n = 56$), was similar to the maize-bean cluster (Figure 2b). This cluster was dominated by those cultivating sunflower, vegetables, groundnuts, mug beans, cassava and some maize in the lowlands (700–1000 m.a.s.l), with mixed inputs of manure and agrochemicals. The fourth, 'coffee farmer cluster' ($n = 22$), was distinct (Figure 2b) and included coffee farmers of the midland (1000–1200 m.a.s.l) and highland (1200–1800 m.a.s.l) zones, mainly on the eastern slopes ($\chi^2 = 49.13$; df = 3; $p < 0.0001$). More than 77% of respondents in this cluster engaged in collective action. The mean age in this cluster was 64, higher than that of the banana (58), maize-bean (56) and other crops-maize farmer (52) clusters.

The clusters also differed significantly in goat ownership (KW = 21.5; df = 3; $p < 0.0001$), income from livestock (KW = 10.37; df = 3; $p = 0.016$), income from selling food crops (KW = 10.58; df = 3; $p = 0.014$ for all) and income from selling cash crops (KW = 83.55; df = 3; $p < 0.0001$). There were no significant differences among clusters in other variables (Table S2).

4.2 | An integrated characterization of farming systems

The three main farming systems were: Maize-bean (with more mixed cropping as a sub-type, Figure 2b), traditional banana homegarden (hereafter homegarden) and coffee agroforestry (hereafter coffee). While we name these systems after the priority crop, they are diverse and typically contain multiple crops, especially homegardens (see Table S8). The three farming systems matched the three types of agricultural plots for the farmer interviews, providing confidence that detailed results from the farmer interviews can be extrapolated to Kilimanjaro. Each system's description integrates data on: (1) farmers' perceptions of the impacts of farming practices on biodiversity, soil conditions and yield (Table 2); (2)

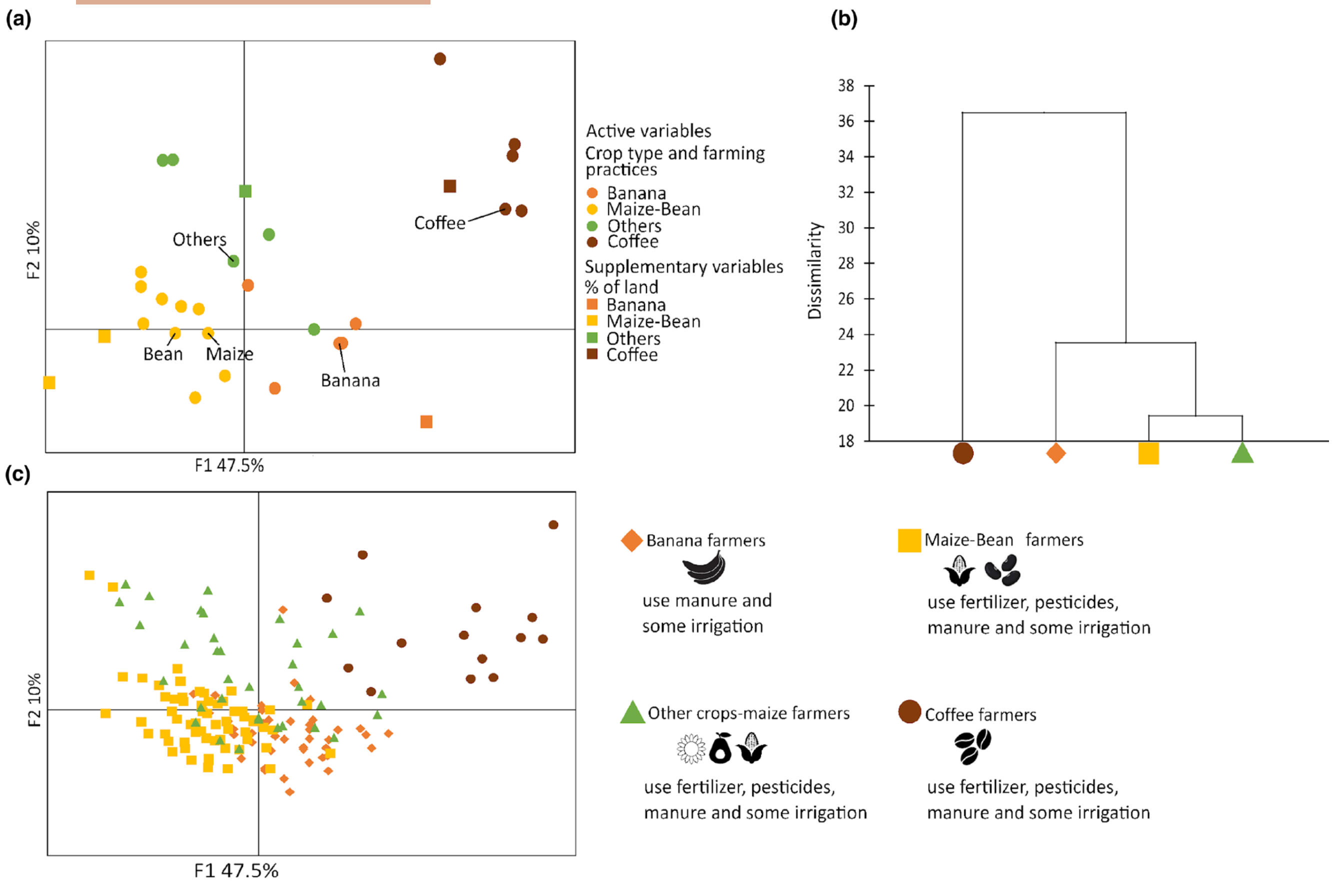

FIGURE 2 Clusters of farming systems in southern Kilimanjaro. (a) Biplot of principal coordinates showing associations between crop types and farming practices, based on Multiple Correspondence Analysis (MCA). The F1 axis explained 47.5% of the variance and distinguished between farmers applying manure, pesticides and irrigation in coffee farming and farmers applying inorganic fertilizer, pesticides and irrigation for beans. The F2 axis, which explained 10% of the variance, distinguished between farmers using inorganic fertilizer, pesticide and irrigation in coffee and those applying manure and pesticides for beans and manure in maize farming. (b) A dendrogram from AHC using Ward's criteria and Euclidian distance as a dissimilarity measure shows the coffee cluster as the most distinctive, while maize-bean and other crops-some maize clusters are the most similar. (c) Biplot of four farmer clusters as identified in (b).

triangulation of the perceptions with the findings of 12 ecological studies conducted on the same agricultural plots (Table S4); (3) indicative profitability from cost–benefit and associated sensitivity analyses (Table 3); and (4) the challenges identified and solutions proposed by key informants. We ground each system's description with quotes from selected findings identified in farmer and key informant interviews, with additional supporting quotes presented in Table S5.

4.2.1 | Maize-bean farming system

Farmers and key informants perceived the maize-bean farming system as relying on intensive agrochemical use, which they noted increased yields and soil fertility but negatively impacted biodiversity. Farmers reported recurring pests such as fall armyworm (Figure 3a). One farmer (MBR16) narrated: '*In the past, there was no need for inorganic fertilizers or pesticides, [...] now it is very different. We cannot cultivate maize without fertilizers and pesticides*'. These observations are supported by systematic reviews of studies from the same plots, showing that intensified systems in Kilimanjaro have lower soil carbon and nitrogen content (Gerschlauer et al., 2019), reduced microbial biomass (Pabst et al., 2013) and accelerated organic matter turnover (Becker & Kuzyakov, 2018). Farmers and key informants attributed increased agrochemical use to declining soil fertility, compounded by challenges such as changing rainfall patterns (i.e. delayed onset and heavy short rains), rainfall shortages, increased pest outbreaks and inadequate agricultural extension support, which further constrained productivity. In the absence of regular farm visits or training from extension officers, farmers rely on locally shared knowledge through informal community networks. For example, farmers reported mixing manure with soil during ploughing rather than placing it in planting holes, to ensure even distribution and reduce the risk of seed damage, particularly when post-sowing rains are insufficient. Key informants and farmers also reported production uncertainties due to increased input costs and volatile markets, as post-harvest local market prices often fall short of government indicative prices. In response to changed rainfall patterns and rainfall shortages, some farmers reported cultivating more drought-resistant crops, such as sunflower and millet, and cultivating only

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TABLE 2 Farming practices undertaken across farming systems and their perceived impacts. We derived the categories of farming practices and descriptions from existing literature.

General practice and description	Specific practices	Number of farmers mentioned the practice (n=5 for each farming system)			Perceived impact				
		M-B	HG	CF	Biodiversity		Soil condition		Yield
Soil and Water Management Practices focused on preserving soil health (erosion control and soil stability) and optimizing soil water availability, with consequences for farm biodiversity, weed control, nutrient management, long-term yield, fertilizer inputs, profitability, and risk.	Water bunds *"Makinga maji"* in Swahili	○	◔	○	△		↑		↑
	Drip irrigation	○	○	●	↗		↗	△	↑
	Furrow irrigation *"Mfongo"* in Chagga	○	◑	○	△		△		↑
	Crop residue mulching	◕	●	●	↑		↑		↑
	Seasonal fallowing	●	○	○	↑		↑		↑
	Vegetation cover	○	○	●	↗		↑		↑
	Tree planting	○	●	●	↑		↑		↑
Nutrient Management Practices to manage and enhance soil stability, fertility, and nutrients to improve yield. These include fertilizer, machinery use, and labour inputs. This has implications for above- and below-ground biodiversity, and soil moisture retention.	Manuring	◑	●	●	↑		↑		↑
	Inorganic fertilizer use	●	○	●	↓	△	↑		↑
	Compost addition	○	○	●	↑		↑		↑
	Reduced tillage	○	◑	●	↑		↑		↑
Pest and Disease Control Practices to manage pests and diseases to reduce crop loss and increase yield while maintaining soil health	Chemical pesticides and fungicides	●	○	●	↓		↓	△	↑
	Organic pesticides	○	○	◕	↑		↑		↑
	Manual and biological control of pests	○	○	●	↘	△	△		↑
	Crop guarding	○	○	◑	×		×		↑
Crop Maintenance and Cultivation Practices related to promoting healthy and diversified cropping systems with improved yield, reduced weeds, increased soil nutrient availability, and the maintenance of farm biodiversity	Hand hoe weeding	●	●	●	↗		↗		↑
	Pruning and desuckering	○	●	●	△	×	△	×	↑
	Removal of old banana plants	○	●	○	↘		↘	△	↑
	Contouring	◕	◕	◑	↑		↑		↑
	Legume intercropping	●	○	○	↗	△	↑	△	↑
Seed source Selection and use of seeds for improved crop performance. Related to seed sovereignty and preservation of traditional seed varieties	Saved or own seed/seedling source	◑	●	●	△	×	△		↑
	Certified improved seeds	●	○	○	△		△	×	↑

Note: ○: no interviewed farmer; ◔: one farmer ($n=1$); ◑: some farmers (2–3); ◕: most all farmers (4); ●: all farmers (5). ↑: positive; ↗: somewhat positive; ↘: somewhat negative; ↓: negative; △: I don't know; ×: none. Multiple symbols in some of the practices refer to different perceived impacts mentioned by the farmers.

Abbreviations: CF, Coffee; M-B, Maize-Bean; HG, Homegarden.

TABLE 3 Sensitivity analysis results on gross margins for the maize-bean, homegarden and coffee farming systems. Baseline gross margins are high across all systems. In the harvest failure (HF) scenario, margins drop by 30%–40% but still cover input costs. Under the sustainable intensification (SI) scenario, increased yields balance out higher input costs, keeping margins stable. However, in the sustainable intensification with shocks (SIS) scenario, margins decrease significantly, with the homegardens experiencing the most severe impact, leading to a negative margin.

Farming system	**Maize-Bean**				**Homegarden**				**Coffee**			
Scenario	Baseline	HF	SI	SIS	Baseline	HF	SI	SIS	Baseline	HF	SI	SIS
Material input costs ($/ha)	80.6	80.6	161.2	161.2	26.4	26.4	52.8	52.8	65.9	65.9	131.8	131.8
Labour costs ($/ha)	111.2	111.2	166.8	166.8	162	162	243	243	875.3	875.3	1313	1313
Total production cost ($/ha)	191.8	191.8	328	328	188.4	188.4	295.8	295.8	941.2	941.2	1444.8	1444.8
Yield (t/ha)	2	0.4	3	1	2	0.4	3	1	2.2	0.4	3.2	1.1
Market price $/t	819	1228.5	819	409.5	430	645	430	215	3040	4560	3040	1520
Total revenue ($/ha)	1660.9	498.3	2491.4	415.2	855.7	256.7	1283.6	213.9	6560.3	1968.1	9840.5	1640.1
Net revenue ($/ha)	1469.1	306.5	2163.4	87.2	667.3	68.3	987.8	-81.9	5619.1	1026.9	8395.7	195.3
Gross margin (%)	86	62	87	21	78	27	77	-38	86	52	85	12

in the long rains, leaving farms fallow during the increasingly unreliable short rains (Figure 3b). Other practices targeted soil condition improvement, for example, crop residue mulching, contouring and legume intercropping (Table 2). The cost–benefit analysis showed a combined mean yield of 2 t/ha for maize and beans, with a positive gross margin of 88% (Table 3). However, the sustainable intensification with shocks scenario indicated a reduction in gross margin to 21%.

Farmer and key informants identified several solutions to overcome challenges in this system (Table 4). These included improved weather information that provides early warnings of low or high rainfall. As one key informant (GOR04) states: '*Dependency on rain-fed agriculture is a gamble, as some years there is not enough rainfall, and some years it rains so much that some crops do not perform well. For example, beans do not require very high rainfall*'. Key informants noted the need for timely and accurate weather information from the Tanzania Meteorological Association to improve farmers' planning. They also note government initiatives to reach out to farmers through digital platforms such as the M-Kilimo app, which provides weather forecasts, market information and agricultural extension support. Key informants also proposed a collective rainwater-harvesting initiative, such as on-farm ponds, because individual groundwater drilling is expensive. They also recommended soil nutrient analysis to provide updated soil information, considering the likelihood of soil exhaustion after many decades of continuous farming. Key informant, GOR02, highlighted this: '*We measured the soil in 2009, and it was discovered that the soil in this ward is more acidic due to former farming practices. Since then, we need further research to know whether the situation has improved and what farmers can do*'. Similarly, farmers expressed that research on recurrent pest outbreaks and loss of pesticide efficacy could improve pest management: '*Some pesticides may initially prove effective but lose their efficacy over time. This inconsistency in pesticide performance can make it difficult to manage pests and diseases effectively. The Tanzania Bureau of Standards must ensure these inputs meet appropriate standards, or researchers can look into it to see if the pests have become resistant*', MBR05. Key informants also suggested shifting from inorganic to organic pesticides to mitigate environmental and human health impacts. Finally, farmers and key informants strongly emphasized the importance of government support through subsidies: '*The government should invest in agriculture to ensure food security and income for local farmers through subsidy programs, as in the past*', GOR01. The government has resumed this initiative that ceased in 2016, with some farmers reporting receiving seed and inorganic fertilizer subsidies in 2023.

4.2.2 | Traditional banana homegardens farming system

Homegardens were perceived as a sustainable and culturally significant farming system by both farmers and key informants. Farmers perceived that most of their practices increase yield and improve soil conditions without damaging biodiversity. These practices focused on soil, water and nutrient management, for example, use of water bunds, furrow irrigation (Figure 3c), crop residue mulching (Figure 3d), tree planting and manuring (Figure 3d). The farmer's perceptions are consistent with ecological studies of the plots showing that homegardens support high pollinator diversity (Classen et al., 2015), possess a high potential for tree regeneration (Renner et al., 2022) and sustain bird and bat species richness due to the presence of fruit-bearing trees and complex vegetation structures (Helbig-Bonitz et al., 2015; Vogeler et al., 2022). Unlike the maize-bean farming system, farmers in homegardens widely apply manure but not inorganic fertilizers. In this system, the gross margin was 78% under the baseline scenario, where labour input costs accounted for 86% of all costs (Table 3). Removing labour costs, the

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FIGURE 3 Photos representing some of the reported challenges and farming practices across farming systems. (a) Pest damage by fall armyworm in maize plant; (b) seasonal fallowing in maize field; (c) furrow irrigation in homegarden; (d) crop residual mulching and manure in homegarden; and (e) vegetation cover between coffee plants. Photo credits: (a, e) Koggani D. Koggani, (b) Eugenia Degano, (c) Berta Martín-López and (d) Neema R. Kinabo.

gross margin increased to 95%. The sensitivity analysis also showed that the gross margin becomes negative (−38%) under the scenario of sustainable intensification with shocks. Yet, homegardens may persist in the face of low financial returns as there is pride in owning a homegarden as expressed by key informant GOR01: *'[...] For the farmers, maintaining homegardens is respecting forefathers and the identity of Chagga's in Kilimanjaro'*.

Farmers and key informants reported biophysical and infrastructure-related challenges in homegardens (Table 4). Farmers reported rainfall shortages as a major barrier to productivity because the use of traditional furrows is declining due to low water discharge from reduced rainfall and poor furrow maintenance. Similarly, poor road conditions during the rainy season made villages inaccessible, reducing farmers' ability to transport produce to markets or forcing them to accept lower prices from local buyers through farm-gate sales. Farmers reported that farm-gate prices were generally low, and bargaining success varied among farmers, depending on the type of banana, size and season. To improve market access, collective bargaining power and reduce transaction costs, key informants proposed improving rural road infrastructure and leveraging existing Agricultural Marketing Cooperative Societies (AMCOS), although they acknowledged some challenges. As one mentioned: '*There are plans to collect bananas, maize, beans, and avocado, too. Once we tried collecting millet, the price in the market was very low, which was discouraging to farmers*', GOR03.

4.2.3 | Coffee agroforestry

Farm managers described coffee agroforestry as a system striving for sustainability and higher yields while aiming to reduce input costs. Farm managers reported a focus on pest and disease prevention, as well as soil, water and nutrient management practices, which were perceived to increase yields with minimal negative impact on biodiversity and soil (Table 2). For pest and disease prevention, farm managers reported propagating coffee seedlings from high-performing, disease-resistant coffee plants. One explained, '*For the past 10 years, there have been significant changes in the coffee varieties used. Initially, seedlings were obtained from the Tanzania Coffee Research Institute. However, over time, a selection process was implemented to identify the best-performing coffee stems with the potential for high production and resistance to pests and diseases [...] Coffee seedlings are now chosen from in-house sources, prioritizing resistance to pests and diseases and their suitability for high production*', CFR10. Similarly, they conducted routine scouting, pruning, desuckering, the use of organic pesticides,

TABLE 4 Challenges, proposed solutions, actors and implementation levels in the three farming systems.

Challenge category	Specific challenge	Farming system(s)	Proposed solution(s)	Actors proposing the solution(s)	Implementation level
Biophysical constraints	Rainfall shortage and changes in the rainfall pattern	M-B	Establish collective water harvesting systems	Farmers	Institutional
			Plant drought-resistant crops	Key informants	Farm
		CF	Use drip-irrigation	Farmers	Farm
		All systems	Improve weather forecast information	Farmers and key informants	Institutional
	Pest outbreaks and diseases	M-B	Research on pests' resistance to pesticides	Farmers	Institutional
		CF	Propagate coffee-seedling	Farmers	Farm
	Low soil fertility	M-B	Conduct soil nutrient analysis	Key informants	Institutional
			Use organic pesticides	Key informants	Farm
Production costs and market constraints	High agrochemical input costs	M-B	Revive subsidy programmes	Farmers and key informants	Policy and government
			Establish organic produce incentive schemes	Key informants	Policy and government
		CF	Use manure and compost from coffee husks	Farmers	Farm
	Unreliable market and price	M-B and HG	Regulate market channels	Key informants	Policy and government
			Leverage Agricultural Marketing Cooperative Societies (AMCOS)		Institutional
	High tax	CF	Introduce tax reduction mechanism	Key informants	Policy and government
Infrastructure limitations	Poor irrigation infrastructure	HG	Maintain the traditional furrow irrigation system	Key informants	Institutional
	Poor feeder road		Improve road access	Key informants	Policy and government
Gaps in agricultural extension support	Lack of technical assistance	M-B and HG	Knowledge sharing through informal community networks	Farmers	Institutional
			Use M-Kilimo app	Key informants	Policy and government
	Unreliable weather forecast	All systems	Improve weather forecast by the Tanzania Meteorological Association	Key informants	Institutional

Note: Implementation levels are categorized into farm-level practices: Actions that can be implemented directly by individual farmers or collectively with minimal external coordination; institutional-level interventions: Require support or coordination from cooperatives, agricultural extension support or local collective action; policy and government-level interventions: Require policy action, funding, or regulation at district, regional or national level.

Abbreviations: CF coffee; HG, homegarden; M-B, Maize-Bean.

biological control (noting chameleons as important) and manual control. Farm managers also reported targeted stem spraying with chemical pesticides or fungicides when pests and diseases persisted.

Farm managers reported other practices, such as the use of manure and compost derived from coffee husks, manual weed removal with the removed weeds placed near coffee stems to serve as mulch, maintenance of plant cover between coffee rows (Figure 3e) and the planting of trees within and around plantation perimeters, as well as implementing drip irrigation for efficient water use. Farm managers considered most practices important for both productivity and environmental stewardship. This corresponded with findings from ecological studies on the plots, which found coffee agroforestry systems to support high dung beetle abundance (Gebert et al., 2020), high phytophagous beetle richness (Njovu et al., 2021) and relatively high abundance of pollinators and other beneficial arthropods (Röder et al., 2017). However, these studies also indicate that the conversion of natural forest to agroforestry leads to a reduction in above-ground carbon stocks (Ensslin et al., 2015).

Based on the cost–benefit analysis, the coffee system had the highest input costs (Table 3). However, the availability of financial resources to cover these and the high market value resulted in a high gross margin (86%). Note that lease costs, which may be significant since the plantations rent the land, are not included. Labour costs, especially coffee picking, accounted for 94% of the input costs. Sensitivity analysis also showed a far lower gross margin of 12% under the sustainable intensification with shocks scenario.

Alongside similar biophysical challenges to those mentioned previously for maize-bean and homegarden systems, coffee farm managers raised concerns regarding high taxes (Table 4). '*We struggle with the burden of high taxes, which can significantly impact our operational costs and profitability. If not effectively managed, these taxes can pose financial challenges for the estate*', CFR17. Farm managers thus suggested lower taxes on coffee sales as a solution.

5 | DISCUSSION

In Kilimanjaro, we categorized and characterized three main farming systems: maize-bean, homegardens and coffee, which demonstrated both shared and distinct farming practices (Table 2). While all systems were estimated to be profitable under favourable conditions, they also appeared sensitive to environmental and market-related shocks (Table 3). Farmers and key informants reported largely similar challenges across the three systems, and these were related to (1) biophysical constraints, (2) production costs and market constraints, (3) infrastructure limitations and (4) gaps in agricultural extension support (Table 4). Proposed solutions to overcome these challenges spanned multiple levels, from the farm-based actions to institutional and policy interventions. At the farm level, practices such as manuring and biological pest control were identified as low-cost and offering multiple benefits. Strategic shifts in crop selection, including the adoption of drought-resistant varieties and improved agricultural information, were also proposed. At higher levels, suggested options included subsidy programmes, organic produce incentive schemes, market regulation, leveraging cooperatives, tax reduction mechanisms and improved agricultural information. Together, these findings highlight the importance of employing a range of disciplinary tools and knowledge types to understand the multi-scalar and multi-dimensional nature of the challenges in farm systems sustainability, and to identify actionable and locally grounded solutions.

5.1 | Heterogeneity of farming systems and practices in Kilimanjaro

Changes in smallholder farming systems often emerge as adaptive responses to shifting socioeconomic needs, environmental pressures and long-term livelihood strategies (Giller et al., 2021; Morton, 2007; Soini, 2005b; Tittonell, 2014). In Kilimanjaro, the heterogeneity of maize–bean intercropping, banana-dominated homegardens and coffee agroforestry systems and practices therein reflects not only fragmented land use but also long-term adaptation to both environmental conditions and socio-economic needs. This can be exemplified by the increasing prominence of maize cultivation in mid- and highland zones, areas once dominated by smallholders' homegardens and coffee cultivation (Tables S2 and S5). This shift is related to the declining ownership of lowland farms, where farmers primarily cultivated maize, and changes in dietary preferences (Ichinose et al., 2020). Several practices were also perceived to improve soil conditions and minimize negative impacts on biodiversity. Some practices, for example, legume intercropping, seed sovereignty, integrated pest management through biological control, reduced tillage, manure and mulch application, which were also reported in our study (Table 2), are considered low-cost and sustainable (Dallimer et al., 2018; Kremen, 2020; Ngosong et al., 2019). This tallies with the newly launched National Ecological Organic Agriculture Strategy of Tanzania for 2023–2030, which highlights that these practices have long been employed to advance multiple goals such as livelihood diversification, soil fertility maintenance and sustainable land use (URT, 2023, p. 3). At the farm level, these same practices provide multiple benefits, including increased and sustained crop production and the maintenance of biodiversity, which provides services such as pollination and soil fertility (Dallimer et al., 2018; Kremen & Miles, 2012). Other practices mentioned in our interviews, such as shifting to drought-tolerant crops like millet or using drip irrigation, illustrate endogenous pathways for making farming systems climate-resilient, a strategy often advocated globally (Ewert et al., 2023; Liniger et al., 2011; Peterson et al., 2018).

Nevertheless, trade-offs exist between achieving socio-economic goals and preserving the land resources that underpin agricultural productivity. Studies have shown that while agricultural expansion can increase yields or incomes, this can come at the expense of biodiversity, soil quality or water resources (Ewert et al., 2023; Lin, 2011; Neyret et al., 2021). These trade-offs can be stark in mountain smallholder systems, such as those on Kilimanjaro, which face climate variability and market instability, and where the need to secure livelihoods can override long term sustainability (Pretty, 2018). Our findings reveal that homegardens and coffee agroforest systems primarily rely on low external inputs and practices that support ecological functions to enhance productivity (Classen et al., 2014; Gebert et al., 2020; Helbig-Bonitz et al., 2015; Njovu et al., 2021; Renner et al., 2022), aligning with calls for agroecological intensification in smallholder landscapes (Pretty, 2018). However, the maize–bean system highlights a more common trade-off situation where farmers heavily depend on agrochemicals (Table S4) to secure short-term yields, which undermines soil biota and nutrient cycling (Gerschlauer et al., 2019; Ndossi et al., 2020; Pabst et al., 2013). As a result, farmers may be locked into an input-dependent system (Berger et al., 2025), potentially increasing their vulnerability to rising input costs, market fluctuations and climate shocks, while further reducing long-term soil fertility and system sustainability (Touch et al., 2025).

While our economic profitability estimates were coarse and only indicative, all farming systems in the study appeared to be profitable under favourable socio-economic and environmental conditions. However, this profitability was vulnerable to environmental and market-related shocks (Table 3), a common feature in smallholder farms (Morton, 2007; Ricart et al., 2023; Soini, 2005b). In Kilimanjaro, such vulnerability became evident when declining global coffee prices, removal of government support through subsidies, market liberalization and droughts, drove many farmers, who were once reliant on coffee as a major source of income, to abandon coffee cultivation (Maghimbi, 2007; Soini, 2005a; Wagner et al., 2021). It is also important to note that many smallholder farmers supplement their farm income through off-farm activities such as small businesses, casual labour or remittances (Anang & Yeboah, 2019; Cuni-Sanchez et al., 2019). These additional income streams help cushion yield failures (Cuni-Sanchez et al., 2019). They may also partially explain why farmers continue to preserve systems like homegardens, which show lower economic returns (Table 3), but are valued for their cultural identity and contributions to livelihoods. Furthermore, while the cost–benefit analysis and other data sources, such as the farmer interview, offer valuable insights from farmers and key informants, we recognize that responses may be affected by recall bias, social desirability or local norms (Bispo, 2022). These influences are typical in social research, particularly when respondents are asked to recall information that they do not typically document, or when questions touch on sensitive practices that may prompt respondents to present themselves in a favourable light. This highlights the importance of interpreting the results in conjunction with other forms of evidence, as we have done here.

5.2 | Local perspectives for holistic farming systems understanding

Studies on SESs emphasize that solutions to environmental and livelihood challenges must be co-informed by the knowledge of farmers, local institutions and policy actors (Chabay et al., 2018; Folke et al., 2016). Our results from Kilimanjaro provide a compelling example of this integrated knowledge in action. It revealed multiple challenges affecting different components of the farming systems and pinpointed both general and system-specific options to promote sustainability. While some challenges, such as low and unreliable rainfall, declining soil conditions, pests and diseases, and unreliable markets, were reported across two or all farming systems, the proposed solutions often reflected the specific context of each system. For example, indicative pricing was recommended for maize–bean crops, whereas leveraging existing cooperative societies was suggested for the banana crop to capitalize on market opportunities through supply contracts and increased bargaining power. This recommendation is supported by broader evidence showing that more than 50% of farmers' organizations improve farmers' income, while 20% increase crop yield and product quality (Bizikova et al., 2020).

Most proposed solutions were practical, farm-level interventions grounded in farmers' experience, such as mulching, drought-resistant varieties or manual pest control. In contrast, other solutions, particularly those identified by the key informants, were more systemic, such as policy support through subsidies or incentive schemes for organic produce, including price premiums and certification initiatives. The National Ecological Organic Agriculture Strategy of Tanzania highlights systemic pathways by emphasizing collective grower group certification as a cost-effective approach. With early support from specialized certifiers, this approach can expand smallholders' access to global markets and strengthen their competitive position (URT, 2023, p. 17).

Furthermore, some solutions were knowledge-based; maize-bean farmers suggested utilizing experiential and experimental local knowledge to enhance soil fertility and prevent seed damage (refer to the example in Section 4.2.1). Such local knowledge may be disseminated through demonstration farms operated by small groups representing different genders and age groups (women, youths and older individuals), thereby facilitating the transfer of collective knowledge across generations and social roles (Mazid et al., 2016). This approach is relevant, as interviews revealed that farmers rely on informal community networks for knowledge sharing due to limited access to formal agricultural extension services, leading them to perceive the government as insufficiently supportive. Although the Ministry of Agriculture has developed the 'M-Kilimo app' to help farmers access relevant agricultural and market-related information, no farmers reported being aware of its existence (Table 4; Table S5). This lack of awareness may be attributed to the app's limited rollout and promotion, low digital access in rural areas and challenges in integrating mobile platforms into existing agricultural extension support in Tanzania (Paschal et al., 2025). Other solutions require collective effort; for example, maize–bean farmers suggested water-harvesting technologies. Such collective action in water management can promote joint adoption and the development of new strategies that stimulate sustainable farming (Shiferaw et al., 2009; Tamburino et al., 2020). These farmer suggestions align with the goals of the Sustainable Agriculture Tanzania initiative and the National Ecological Organic Agriculture Strategy of Tanzania (URT, 2023), which emphasize reliable water access as critical for agroecological systems amid increasing drought and irregular rainfall, and highlight the need to develop appropriate irrigation infrastructure and promote sustainable water use tailored to farmers' needs.

These differing solution levels, rather than being contradictory, offer complementary entry points for understanding how to sustain farming systems. First, they reflect the need for multiscale interventions, where farm-level practices, institutional support and policy actions must interact to address the sustainability challenge facing farming systems across social, ecological and economic dimensions (Ewert et al., 2023; FAO, 2021). Second, they underscore that sustainability research is not solely about improved practices and better policies, but also about grounding solutions in the knowledge and lived experiences of those most affected (FAO, 2021). As this study shows, engaging both farmers and key informants reveals what is practised and what is perceived as necessary to sustain production and manage uncertainties (FAO, 2021; Ricart et al., 2023). This is especially critical in contexts where formal monitoring systems and data may be limited, yet experiential knowledge offers rich insights into environmental change and livelihood dynamics (Šūmane et al., 2018; Swart et al., 2023).

More broadly, this study demonstrates that the wider call for knowledge integration in human–nature relations and sustainability science (Norström et al., 2020) is directly relevant to the management of farming systems as SES. By combining farmers' experiential knowledge of practical constraints, ecological evidence on biodiversity and soils, and economic assessments of profitability, we show that pathways towards sustainability emerge from the interaction of multiple knowledge types and disciplines rather than from any single perspective. By elevating farmer perceptions and cross-validating these with ecological measurements, the study also advances the idea that different knowledge types can complement and strengthen each other. Such explicit integration of knowledge types remains uncommon in agricultural sustainability research (Djenontin & Meadow, 2018), hence we illustrate how knowledge co-production principles, such as being context-based, pluralistic, goal-oriented and interactive (Norström et al., 2020) can manifest through integrated research approaches.

6 | CONCLUSION

Farming systems in Kilimanjaro and beyond are dynamic, shaped by farmers' knowledge and practices as they adapt to emerging challenges while striving to sustain both livelihoods and land resources (Darnhofer, 2014; Ewert et al., 2023; Folke et al., 2010). Our study demonstrates how an interdisciplinary approach, integrating plural knowledge sources and types from social, ecological and economic dimensions, can capture the complex realities of farming systems in ways that monodisciplinary studies cannot. By combining farmers' perspectives with ecological research findings, we identify context-specific solutions that consider local practices embedded in farmers' lived realities while highlighting the structural support needed to sustain both the ecological basis underpinning the functioning of farm systems and the farmers' livelihoods. As a consequence, these solutions may prove to be the foundations of actionable pathways towards sustainable agriculture.

AUTHOR CONTRIBUTIONS

Neema R. Kinabo and Peter Manning conceived the study, Neema R. Kinabo and Koggani D. Koggani collected the data, and Neema R. Kinabo and Berta Martín-López performed the analyses. Neema R. Kinabo led the manuscript writing with input from Dominic A. Martin and Peter Manning. All authors contributed to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Farmer survey data will be available at (Kinabo, 2025). Farmer and key informant interview data will not be made available publicly for reasons of interviewee confidentiality.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Figure S1. Overview of farming practices for major crops as identified in the farmer survey (n=306) for contextualizing the more detailed cluster-specific analysis that followed.

Table S1. Population size (N), sample size (n), and sampling error at a confidence level of 95%.

Table S2. Mean values and statistical differences regarding socio-demographics, geographical location, and farming characteristics are shown for each cluster.

Table S3. The results of the ANOVA followed by the Bonferroni test show significant differences between axes F1, F2, F3, and F4 across clusters.

Table S4. Overview of ecological study findings in southern Kilimanjaro with data collected from the same agricultural plots used for farmer (smallholder and farm managers) interviews.

Table S5. Themes and quotes from thematic analysis of qualitative information from farmer and key informant interviews.

Table S6. Socio-demographics of respondents who participated in the farmers' survey (n=306) and average farm size along the altitudinal gradient.

Table S7. Factor scores from the Multiple Correspondence Analysis (MCA).

Table S8. Percentage co-occurrence of crops based on farmers' top three priority crops.

Appendix S1. Farmer survey.

Appendix S2. Farmers interviews questions guideline.

Appendix S3. Crop yield assessment, assumptions and variables included in the cost-benefit analysis and sensitivity analysis.

Appendix S4. Field observations guideline.

Appendix S5. Methodological approach for reviewing ecological literature to triangulate biophysical measures with farmers' perceptions of the impact of farming practices on biodiversity, soil conditions, and yield.

Appendix S6. Key informant interview guiding questions.

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