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REVIEWED BY
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Melanie Requier,
CIHEAM, France

*CORRESPONDENCE
Anne W. Kuria
A.Kuria@cifor-icraf.org

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Revisiting agroecological transitions in Rwanda a decade later: the role of local knowledge in understanding the crop diversity–food security–land degradation nexus

Anne W. Kuria[1,2]*, Tim Pagella[2], Catherine W. Muthuri[1] and Fergus L. Sinclair[1,2]

[1]Agroecology Theme, World Agroforestry (ICRAF), Gigiri, Nairobi, Kenya, [2]School of Environmental and Natural Sciences, Bangor University, Bangor, Gwynedd, United Kingdom

The challenge of achieving food security amidst broken food systems, the climate crisis, biodiversity loss, degrading land, and growing social inequity remains a critical development priority in alignment with the Vision 2030 agenda. While crop diversification is a cornerstone of agroecological transitions and food security, global food systems have often overlooked its potential, largely due to insufficient local participation and the reliance on blanket policies unsuitable for heterogeneous contexts. This article revisits agroecological transitions in Western Rwanda a decade after data collection, assessing the enduring relevance of local knowledge in understanding the crop diversity–food security–land degradation nexus. Using a systematic knowledge-based approach (AKT5), data were collected from 150 smallholder farmers through a Paired Catchment Assessment. Findings from the 1995–2015 period revealed a decline or disappearance of "low-value" crops, driven by the Crop Intensification Program (76%), land shortages (55%), and abandonment of slow-growing crops (49%). As a result, 83% of farmers reported food insecurity, primarily manifesting as seasonal food shortages (51%). Perennial crops emerged as critical for bridging hunger gaps, while reduced crop diversity forced many farmers to rely on off-farm food sources. The original analysis identified seven agroecological principles integral to the crop diversity–food security nexus: soil health, biodiversity, synergy, economic diversification, social values and diets, co-creation of knowledge, and participation. These findings varied significantly by land degradation status, emphasizing the importance of context-specific solutions. This study also showed that farmers have become more dependent on sourcing food off-farm, with food produced on-farm supporting farmers for an average of 6.6 months annually in 2015 compared to 10.1 months in 1995. This underpins the need to leverage ecological rather than administrative boundaries, ensuring connectivity within food systems, and fostering equitable trade mechanisms for smallholder farmers if agroecological transitions are to be realized. A decade later, the findings of this study were reflected upon and validated through recent literature, which underpins the validity of local knowledge in understanding of agroecological transitions. This advocates for stronger integration of local knowledge, stakeholder collaboration to promote the co-design of tailored context-appropriate, inclusive, and sustainable policy frameworks to foster sustainable food systems across scales.

KEYWORDS

local knowledge, crop diversity, agroecology, food security, land degradation, smallholder farmers, knowledge co-creation

1 Introduction

Crop diversity plays a critical role in steering agroecological transitions towards meeting the various dimensions of food security needs across heterogenous and multi-functional agricultural ecosystems. Sustainable agriculture and food systems that are achieved through agroecology simultaneously offer multiple benefits to society (Nicholls and Altieri, 2018). This is because agroecology promotes a shift from generalized to customized production systems and promotes ecological, social, economic and nutritional diversity of systems (Wezel et al., 2020). Agroecological approaches including principles and practices thus utilize comprehensive ecological, economic, and social principles in the transition of small-scale farming systems, with the aim of enhancing their resilience (Savels et al., 2024; Ume et al., 2023). This involves tailoring 13 universal agroecological principles (recycling, input reduction, soil health, animal health, biodiversity, economic diversification, social values and diets, fairness, connectivity, land and natural resource governance; and participation) to suit specific local conditions (HLPE, 2019; Sinclair et al., 2019).

Multifunctionality of agricultural systems is enhanced through the increased functional diversity of crop polycultures (Cordeau, 2024; Finney and Kaye, 2017). Agroecological ecosystems comprising of diverse crop species produce multiple ecological goods and services and contribute to their continuous regeneration and resilience compared to less diverse systems (Kahiluoto, 2020; Matsushita et al., 2016). There is evidence that intercropped systems are more ecologically and socio-economically resilient compared to monocrops (Bowles et al., 2020). Combinations of crops is thus beneficial as it contributes significantly to ecological synergies as each crop performs a specific function within the agricultural ecosystem and also results into beneficial interactions amongst crops being grown (Franco et al., 2015). Further, not only is diversity critical at the species level but also at the genetic level as crop genetic diversity leads to long-term agroecological resilience and stability of ecosystems such as through climate-resilience and pest and disease resistance (Jacques and Jacques, 2012; Sanya et al., 2020).

Integrating perennial crops with annual crop species is a particularly effective strategy for increasing on-farm crop diversity. This ensures that while annual crops provide short and mid-term services such as food, feed and fuel; perennial crops can provide long-term multiple environmental services such as soil nutrient cycling, carbon sequestration, ground water recharge, pest and disease control and enhanced crop pollination (Bowles et al., 2020; Muthuri et al., 2023). Ndoli et al. (2021) found a positive correlation between perennial crop diversity and food security. Different perennial crop species have for example been found to favor different beneficial soil macrofauna species (Kamau et al., 2017). This includes facilitating soil aggregation resulting from enhancing soil microbial community composition (Tian et al., 2019). When it comes to perennial crops, Endale et al. (2017) notes that for systems to operate optimally and in order to generate sufficient ecological goods and services, there is need to not only increase species richness but also abundance.

In Rwanda like in most rural sub-Sahara Africa communities, where smallholder farmers rely on agriculture for their livelihoods, food security is closely tied to crop diversity. Empirical studies suggest that diverse cropping systems contribute to food security by enhancing availability, access, utilization, and stability (Mango et al., 2018; Mengistu et al., 2021). Furthermore, crop diversity has been closely linked to dietary diversity, providing essential micronutrients that improve health outcomes (Nicholson et al., 2021; Rajendran et al., 2017). Despite high crop diversity playing a key role in steering agroecological transitions towards meeting through enhancing food security, productivity and resilience of agricultural systems (Bourke et al., 2021), majority of development efforts in sub-Sahara Africa countries including Rwanda have mostly focused on enhancing productivity and closing yield gaps of a few selected mono-crops (Kim et al., 2022; Schrama et al., 2018). While majority of largescale farms across the world are simplified by monocrops, majority of smallholder farms especially in sub-Sahara Africa are mostly characterized by complex and diverse cropping systems (Osbahr and Allan, 2003). Studies have shown that smallholder farms are highly heterogeneous ecologically, social-economically, biophysically, historically and politically (Kuria et al., 2024; Vanlauwe et al., 2014). Hence the systems hold varying crops and crop diversity trends; and populations experience different types and levels of food insecurity and have varying vulnerability levels. Agriculture and food systems thus need to adapt to different contexts by adopting agricultural management practices to enhance crop diversity.

Secondly, despite food insecurity being multifaceted and drivers originating from multiple scales (Marchetti et al., 2020), majority of policy makers have often designed food security policies at coarse scale, either at the global, regional or national level (Duncan et al., 2022; Lele et al., 2013). Majority of food security metrics and indicators used are often generated through top-down approaches that are generalized across heterogeneous landscapes. Top-down coarse approaches take away the target population, who understands their local agroecological system intricately, from being part of solutions aimed at improving food security (Duncan and Claeys, 2018). This results in inappropriate, unsustainable and skewed interventions and the inability to meet all the dimensions of food security (Burchi and De Muro, 2016; De Haen et al., 2011). This leads to lack of customization of food security policies and programs to local context, which is mainly caused by the lack of co-creation of knowledge and failure to incorporate knowledge of local food producing communities in understanding the target context for which food policies and programs are being designed.

The urgency to adapt agricultural systems to current and emerging challenges—such as land degradation, climate change, population pressures, and disruptions like the COVID-19 pandemic—has heightened calls for agroecological transitions (Jha et al., 2021; Kumar et al., 2021). These transitions emphasize the need for context-appropriate policies that integrate local knowledge and address the specific needs of diverse communities, including marginalized groups such as women and children (de Araújo Palmeira et al., 2020; Singh et al., 2020).

Local knowledge refers to locally derived understanding which is based on experience and observation; and it is usually a mixture of traditional knowledge, knowledge acquired from external sources (education, media, dialogue with other communities) and contemporary learning (Dixon et al., 2001). Unlike scientific knowledge, which is often formalized and generalized, local knowledge is embedded in social structures, oral traditions, and cultural contexts (Agrawal, 1995). It is dynamic and evolves through experiential learning and adaptation to changing conditions, such as climate variability and shifting agricultural policies (Chambers, 2012). The process of translating local knowledge into scientific discourse is not merely an act of documentation but involves interpretation and contextualization to ensure that indigenous meanings and practices are preserved (Smith, 2012).

There is wide agreement on the need to change the prevalent generalized agricultural models, given their negative impacts and their incompatibility with current societal needs and dynamic context. There have been many calls for an agroecological transition to respond to food shocks and crises resulting from conventional generalized food systems to context-appropriate food systems (Sinclair et al., 2019). Agroecological transition has been promoted as a potential solution to the ecological, social and economic problems generated by these models. However, there is limited knowledge on the role of local knowledge in understanding the complex role that crop diversity plays in the context of food insecurity from an agroecology perspective.

Therefore, the overall objective of this study was to co-create knowledge on crop diversity and food security by integrating local knowledge with scientific perspectives. This study revisits agroecological transitions in Rwanda, a decade after data collection, to assess the effect of changes in crop diversity on food security. Specifically, it addresses three key hypotheses: (1) on-farm crop diversity has decreased over time, influencing food security status; (2) local knowledge enhances understanding of agroecological principles related to the crop diversity–food security nexus along a land degradation gradient; and (3) farmers have become increasingly reliant on off-farm food sources. By revisiting these dynamics, the study provides insights into the validity and role of local knowledge in designing adaptive, agroecological strategies for food security and sustainability in the face of evolving challenges.

2 Materials and methods

2.1 Study area characterization and selection

This study was undertaken in Gishwati, which falls under Rubavu and Nyabihu Districts of Western Rwanda. Gishwati area is known as Rwanda's food basket due to its sub-humid agroecological zone and rich volcanic soils which makes the area favorable for agriculture (Kabirigi et al., 2017; Kuria et al., 2019). Gishwati forest used to extend towards Lake Kivu at the Border of Rwanda and DRC but currently the forest consists of fragments resulting from deforestation whose drivers were three-fold namely: forest conversion to agricultural land for enhanced food security, settlements and over-extraction of tree products for building and fuelwood for returnees and refugees following the 1994–1995 genocide (Ordway, 2015).

Rubavu and Nyabihu districts are characterized by diverse agroecological conditions and socio-economic structures that influence farming systems and resource management. Both districts face land fragmentation due to high population density, with most farmers cultivating smallholder plots averaging less than 0.5 hectares (National Institute of Statistics of Rwanda, 2022). Land tenure systems include a mix of customary and formal ownership, with increasing formalization through land registration programs. In terms of gender roles, agriculture is the primary livelihood activity in both districts, with both men and women actively engaged. However, women face structural barriers to land ownership and decision-making within agricultural value chains because they often have limited control over land despite their significant role in farming activities, post-harvest processing, and household food security (Uwizeyimana et al., 2021). Gendered labor division also influences access to agricultural resources, training, and markets.

Given its proximity to the DRC, Rubavu has a dynamic agricultural economy, with a mix of subsistence farming and commercial activities. Farmers engage in small-scale trade, particularly in food crops and livestock products. Urbanization and tourism contribute to diversified income sources (Ministry of Finance and Economic Planning, 2020). On the other hand, Nyabihu district is known for high-altitude farming, with a focus on potatoes, dairy production, and agroforestry systems. Limited road infrastructure and market linkages affect farmers' ability to commercialize surplus produce. Government and NGO interventions promote climate-smart agriculture and sustainable land management practices (Rwanda Environment Management Authority, 2019).

This research adopted a Paired-Catchment experimental design (Brown et al., 2005) and focused on three landscapes namely (Degraded, Recovering, Restored). We hypothesized that land degradation status heterogeneities present different sets of biophysical opportunities and challenges for crops and food security, hence unique entry points for agroecological practices (Nkheloane et al., 2012). Hence including landscapes under different degradation status would inform the design of more inclusive and diverse food security options. Historical timelines revealed that although all three study sites underwent simultaneous tree cover loss after the 1994–1995 genocide, they underwent different trajectories of land degradation and restoration (Aynekulu et al., 2014; Bigagaza et al., 2002). The topography of all sites is hilly with steep slopes (some areas have a slope inclination of over 50%), hence the landscape is susceptible to severe soil erosion (Byiringiro and Reardon, 1996; Kagabo et al., 2013). Due to the hilly nature of the landscape, the study thus further stratified each landscape according to slope gradient, which included upslope, midslope and downslope farms. The degraded landscape was characterized by Alisols, which due to their poor structural stability and susceptibility to leaching and runoff are more prone to erosion than Andosols which have a well-aggregated structure (Food and Agriculture Organization, 2015; IUSS Working Group WRB, 2022), which were the dominant soils in the recovering and restored landscapes. The Recovering and Restored landscapes were adjacent to each other and neighboring Karago Lake and were located in Kadahenda cell, Karago sector of Nyabihu district (Figure 1). The Recovering landscape, whose study villages were Karandaryi, Gakoma and Nkomane, falls under the Eastern Congo-Nile Highland Subsistence agro-farming-ecological zone and lies between 2350 and 2540m.a.s.l. with average annual rainfall of 1200–1500mm. It is characterized by alisols and still experiences slight soil loss through surface run-off because it has more recent erosion control interventions (2012) compared to the Restored landscape (2007). The Recovering landscape is receiving soil and water conservation interventions and food security interventions implemented through the Trees for Food Security Project led by the World Agroforestry (ICRAF) through funding by the Australian Centre for International Agricultural Research (ACIAR) and has progressive terraces with trees and other vegetation planted along (Cyamweshi et al., 2021). The project aimed at sustainably improving productivity of farming landscapes, and to recover food

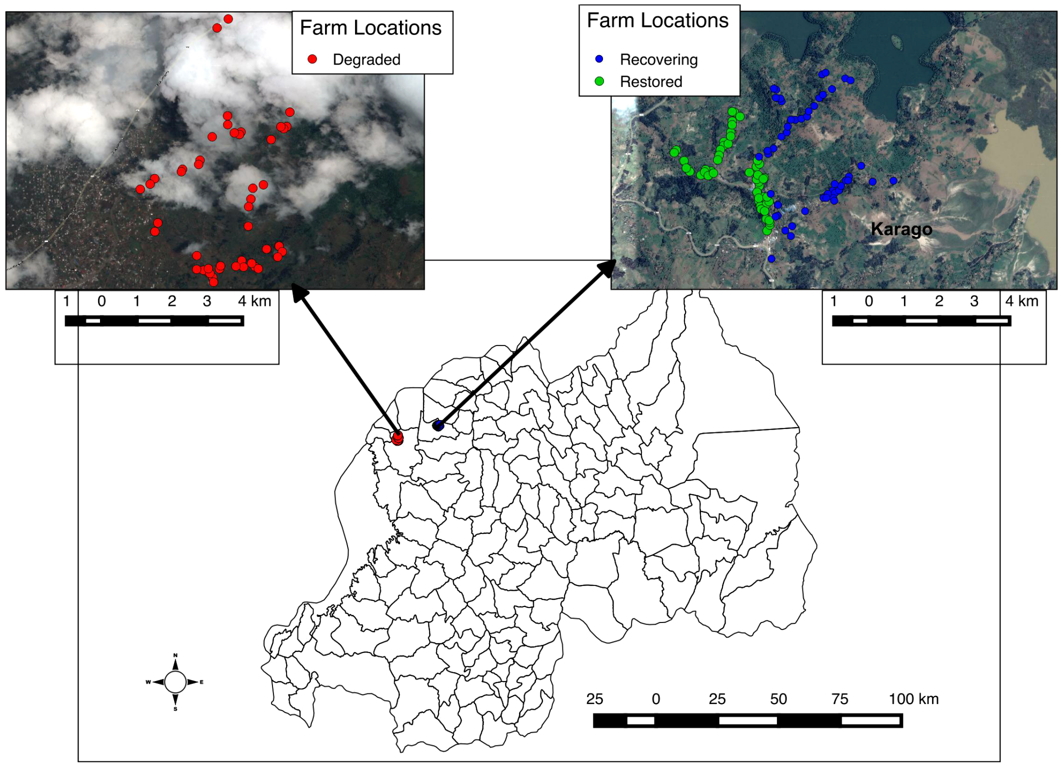

FIGURE 1
Map of Rwanda showing location of fields sampled in Gishwati.

and nutritional security through the promotion of suitable agroforestry interventions.

The Restored landscape (the study village was Gihira), falls under the Eastern Congo-Nile Highland Subsistence agro-farming-ecological zone and lies between 2380 and 2570m.a.s.l. with average annual rainfall of 1200–1500mm. It is characterized by alisols and soil loss had been controlled through soil and water conservation interventions implemented from 2007 namely bench and progressive terraces with vegetation planted along. In 2005/2006, the government of Rwanda through the 'umuganda' community service embarked on soil erosion control as part of the national soil and water conservation program; whereby bench and progressive terraces were established on steep slopes (Bizoza, 2014) and stabilized through planting of *Alnus acuminata* and *Setaria* sp*hacelata*. The interventions were also meant to protect Lake Karago and Busoro river from siltation. In addition, the government set aside 50 meters of land adjacent to the water bodies for planting trees.

The Degraded landscape was in a different farming system located in Gikombe cell, of Nyakiliba sector in Rubavu district. The study villages were: Rushubi, Nyabibuye and Nyakibande. The landscape falls under the North-Western Volcanic Irish Potato Zone, between 1890 and 2180m.a.s.l. with average annual rainfall of 900–1500mm, is characterized by volcanic andosols and has no soil erosion control interventions hence it is characterized by severe soil loss as a result of soil erosion, landslides and siltation as well as frequent flooding in the downslope flat areas. The area has not received any soil and water conservation interventions following the post genocide deforestation in 1995. The upper part of the Degraded landscape is adjacent to Gishwati protected forest while the bottom part borders Mahoko town. After the government of Rwanda evicted farmers who had encroached Gishwati forest in 2010, and soil and water conservation efforts have mainly involved reforestation of the protected forest, and not the adjacent farming landscape, which was the focus for this study.

2.2 Data collection using the agroecological knowledge toolkit methodology

This study adopted a qualitative approach to assess the role of local knowledge in agroecological transitions, particularly in relation to crop diversity, food security, and land degradation. Data were collected through semi-structured interviews, focus group discussions, and field observations with smallholder farmers in Gishwati, Rwanda. The research framework is informed by the 13 agroecological principles proposed by the High-Level Panel of Experts on Food Security and Nutrition (HLPE, 2019), which serve as a guiding framework for transitioning towards sustainable food systems. These principles encompass ecological, socio-economic, and governance dimensions critical to agroecological transformations. During data analysis, we systematically examined how local knowledge aligns with these 13 agroecological principles. Rather than addressing all 13 principles in detail, we identified seven principles that emerged as most relevant to the crop diversity–food security–land degradation nexus based on farmers' experiences and responses. This analytical approach ensures that the findings remain empirically grounded while providing insights into the specific agroecological principles that shape sustainable food system transitions in Gishwati. Accordingly, the discussion section presents these seven principles, highlighting their significance in leveraging local knowledge for agroecological sustainability.

The study employed the AKT5 methodology, a knowledge-based systems approach that systematically integrates quantitative and qualitative research methods to systematically capture and analyze farmers' knowledge on crop diversity and food security (Dixon et al., 2001). While it dates back to the late 1990s and early 2000s (Sinclair and Walker, 1998), AKT5 remains one of the most robust tools for capturing complex, context-specific knowledge systems related to agroecology. This methodology was thus chosen because it allows for structured knowledge elicitation while preserving the richness of farmers' contextual experiences. AKT5 facilitates co-creation of knowledge by combining structured interviews and hierarchical knowledge organization, ensuring that insights from diverse farmers are systematically documented (Walker and Sinclair, 1998). While alternative methodologies such as ethnographic approaches (Agar, 2006; Turner and Berkes, 2006) or participatory rural appraisal (PRA) (Chambers, 2007) have been widely used to capture local knowledge, AKT5 offers a unique advantage in integrating both qualitative narratives and quantitative data, making it well-suited for facilitating the representation of local knowledge in a form that allows for systematic analysis and integration with scientific knowledge, thus contributing towards interdisciplinary agroecological research (Sutherland, 2012).

Furthermore, AKT5 is particularly suited for agroecological research as it enables the identification of knowledge hierarchies, causal relationships, and farmers' decision-making processes regarding land use, crop diversity, and food security (Sinclair and Walker, 1999). Its capacity to capture knowledge heterogeneity across different land-use contexts and social groups made it an ideal choice for our study, which sought to document and co-create knowledge with smallholder farmers in Western Rwanda. While newer methodologies exist, many lack the specificity required for organizing and analyzing local agroecological knowledge in a structured manner. Moreover, the adaptability of AKT5 allows for its refinement and modification in response to contemporary research needs, as demonstrated in recent applications to agroforestry and participatory action research (Coe et al., 2014; Sinclair et al., 2019). Thus, our use of AKT5 is justified by its proven effectiveness, methodological rigor, and adaptability to current agroecological challenges.

This study, which was conducted between August and November, 2015, systematic knowledge-based systems approach (AKT5) (Sinclair and Walker, 1998; Walker and Sinclair, 1998). This involved semi-structured interviews with a stratified sample of 150 willing and knowledgeable informants. The knowledge was then recorded and represented using the AKT5 software (Dixon et al., 2001). The AKT5 local knowledge methodology entails four stages. All the four stages of the elicitation were applied across all three landscapes namely the degraded, recovering and restored landscapes.

The first (scoping) stage of the AKT5 methodology served to establish mutual familiarity between the researcher and the community, creating a foundation for effective knowledge exchange (Figure 2). The scoping stage activities included participatory transect walks to understand and characterize the landscape biophysical, including farm typologies, community resources, annual and perennial crops grown, and degradation hotspots. These factors were then used as variables for stratifying informants, ensuring a more representative understanding of local knowledge systems. Further, this stage allowed for refining research objectives by clarifying the problem and ensuring the knowledge base aligned with the community's needs and local context. The scoping stage also involved elicitation of non-farmer local informants, which was done through Key Informant Interviews with crop-production experts, agricultural extension officers and local administration. Further, six focus group discussions were held 69 farmers from the three landscapes. While having broad discussion about locally relevant ecosystem services, farmers named food provisioning as their top-most priority, hence the focus of this study. From the discussions, it was noted that crop diversity was low, which informed the need to assess the relationship between crops and food security. Seasons cropping calendars (Yang et al., 2019) were also used to elicit information on the periods that crops are available for consumption and identify food shortage months. This was combined with in-depth discussions on the drivers of food insecurity.

The second (definition) stage of the AKT5 methodology focused on establishing a comprehensive understanding of the subject domain by setting clear boundaries, identifying key terminologies, and developing a structured framework. To achieve this, key informants were deliberately selected from the community based on their interest, articulateness, depth of knowledge, and willingness to participate, rather than through random sampling. This consisted of six farmers from each of the three landscapes who were randomly selected for in-depth interviews and probing further on the current food security status.

The third (compilation) stage of the AKT5 methodology focused on systematically documenting detailed knowledge within the framework established during the definition stage while capturing variations in knowledge across the community. Rather than seeking statistically representative samples, this stage prioritized in-depth discussions with a small number of highly knowledgeable individuals. The compilation stage involved an iterative process whereby knowledge elicited from individual farmers was re-evaluated through repeated visits to the same farmers to probe further to get additional information or clarifications; which were then recorded and entered into the AKT5 tool. This process was repeated (at least two visits per farmer) until no new information was obtained from each of the respondents. The repeated interviews with the same informants was crucial for gaining deeper explanatory insights and resolving inconsistencies, making willingness to participate, a key selection criterion. A stratified random sampling approach was used to ensure diverse perspectives on the subject matter. Stratification considered key factors such as gender, location of farms along the slope gradient and age, as these were hypothesized to influence knowledge distribution.

The fourth and last stage, which is referred to as the generalization stage of the AKT5 methodology aimed to assess

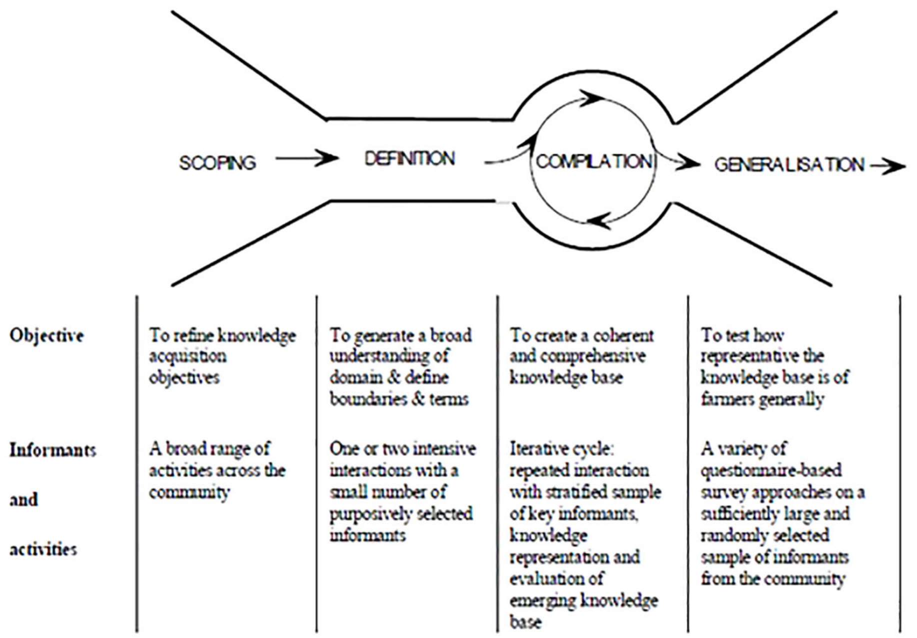

FIGURE 2
An overview of the four stages in the knowledge elicitation process using AKT5 methodology. Source: Dixon et al. (2001).

the representativeness of the knowledge-base obtained from a small group of informants by testing its validity across the broader community. This required a statistically representative random sample, typically consisting of at least 100 individuals who were not previously interviewed. The generalization stage involved formulating key crop diversification – food security research questions based on issues deemed context-relevant based on the in-depth knowledge obtained during the previous three stages. Pre-testing of the questionnaire was then conducted with 12 farmers (four from each of the three landscapes). Once the questionnaire was refined, it was then administered to 150 farmers (50 farmers from each of the three landscapes). The 150 farmers were interviewed for both 1995 and 2015 food security status. Willing farmers were then selected through longitudinal and horizontal transects. The sample comprised of 83 men and 67 women. Results presented here were generated at the last (generalization) stage of AKT5 local knowledge elicitation. The key objectives of this stage included validating the knowledge base to ensure it accurately reflected the community's collective understanding. Additionally, this stage examined how knowledge was distributed among different community members and identified variations in perspectives. It also provided an opportunity to supplement the existing knowledge base with additional details that may have been overlooked during the compilation stage, thereby refining and enhancing the overall understanding of the domain.

The AKT5 methodology is therefore designed to facilitate the systematic elicitation and organization of local knowledge in a way that integrates both qualitative insights and structured analysis (Dixon et al., 2001). By employing a multi-stage approach, AKT5 allowed for an iterative refinement of research questions, ensuring that the final data collection phase captures the most relevant and context-specific knowledge (Walker and Sinclair, 1998). As discussed in the above stages, the initial stages thus involved participatory knowledge elicitation with farmers, experts, and local stakeholders, which helped structure the knowledge base before conducting large-scale surveys (Altieri et al., 2015). While the final stage consisted of individual interviews, it built upon the socially embedded knowledge networks identified earlier, allowing for both individual and collective knowledge processes to be considered. This methodological approach ensured that the study captured the complexity of local knowledge systems, while providing a structured means for comparison with scientific knowledge (Dixon et al., 2001).

Over the years, the AKT5 methodology has however evolved to enhance its applicability in complex agroecological and food system research. Initially designed to systematically structure and analyze indigenous ecological knowledge (Dixon et al., 2001; Walker and Sinclair, 1998), its refinement has integrated participatory validation processes, gendered knowledge systems, and multi-scalar assessments. In our current research revisiting agroecological transitions in Western Rwanda, AKT5 was adapted to capture longitudinal changes in local knowledge across different land degradation contexts. By incorporating a Paired Catchment Assessment and integrating recent literature, this study strengthens AKT5's ability to contextualize crop diversity–food security–land degradation dynamics within evolving policy and environmental challenges (Kuria, 2019). This refinement underscores the importance of local knowledge in shaping adaptive, context-specific, and inclusive food policies, ensuring that agroecological transitions align with diverse socio-ecological realities.

2.3 Data analysis methods

AKT5 tool was used to analyze and qualitatively interpret data and knowledge elicited through the first three stages of the AKT process explained earlier (Sinclair and Walker, 1998; Walker and Sinclair, 1998). It involved breaking down knowledge into unitary statements which were then represented using formal grammar and local taxonomies where applicable. While local taxonomies and qualitative statements captured the depth and context of indigenous knowledge, the process of converting these into variables allowed for comparative analysis and pattern recognition across different knowledge holders and contexts. In this study, the transformation of qualitative statements into variables was conducted with careful consideration of preserving meaning while enabling broader synthesis. This formed a basis for formulating the questionnaire for collecting quantitative data. The Generalization stage data was recorded in Microsoft Excel and was then exported to R statistical software (R Development Core Team, 2013) for further analysis. Frequency statistics (including percentages) were run to show the number of farmers that held knowledge about a specific food security aspect. Results were also presented using bar plots generated using the 'ggplot' function. Due to the categorical nature of the variables, where a stratum had a sample size of at least five, a Chi-square Test of Independence was applied to examine associations and variations in knowledge distribution among different participant groups and determine whether the sample data was consistent with the distribution that had been hypothesized (Mchugh, 2013). This step aligns with the mixed-methods approach, integrating qualitative insights with quantitative validation to strengthen the reliability of findings.

3 Results

3.1 Decreasing on-farm crop diversity trends between 1995 and 2015

We sought to understand whether on-farm crop diversity has changed or remained the same between 1995 (before genocide period) and 2015 (when this study was undertaken). We requested all farmers interviewed to name the food crops they were growing in 2015 and in 1995. Results from the 150 farmers interviewed in Gishwati indicated a notable decrease in the number of farmers growing some of the annual crops or complete disappearance of some annual crops from farms between 1995 and 2015; and inversely an increase in the number of farmers growing perennial crops in 2015 compared to 1995.

A total of 10 annual crops were grown by farmers between 1995 and 2015 (Figure 3). In both years, the main annual crops grown consistently by majority of farmers were beans (94% and 98%) and Irish potatoes (77% and 86%) respectively. However, there were significant differences (p=0.001) in the number of farmers growing sorghum, peas and maize between the two years. In 2015, no farmer was growing sorghum, which was being grown by 68% of farmers in 1995; while only 1% of farmers grew peas, which was being grown by over 50% of farmers in 1995. Maize too was being grown by fewer farmers (35%) in 2015 compared to 1995 (83%). However, no farmer reported growing amaranth in 1995 but it was being grown in 2015 by 15% of farmers.

Seven perennial crops were being grown between 1995 and 2015 (Figure 4). There was an increase in the number of farmers growing avocadoes and tree tomatoes in 2015 compared to 1995, though the differences were not significant. Avocadoes were being grown by atleast 57% of farmers in 2015 compared to 45% in 1995. The number of farmers growing bananas decreased significantly (p=0.05) between 1995 and 2015 while guavas disappeared by 2015. Unlike in 1995, in 2015, farmers were growing cassava (*Manihot glaziovii*), whose leaves played a key role in the nutritional diets of farmers as vegetables ('isombe' in kinyarwanda).

The number of farmers growing some of the annual and perennial crops varied with land degradation status. For annual crops, in both 1995 and 2015, sweet potatoes were mostly grown in the Degraded landscape, while Irish potatoes were mostly grown in the Recovering and Restored landscapes. In 1995, sorghum was mostly grown by farmers in the Recovering and Restored landscapes, while in 2015, maize was mostly being grown in the Restored and Recovering landscapes. However, there was no significant difference in number of farmers growing beans in both years across the three landscapes.

For perennial crops, in both 1995 and 2015, bananas were mostly grown in the Degraded landscape. In both 1995 and 2015, a higher proportion of farmers in the Degraded landscape grew avocadoes compared to other landscapes. In the Recovering and Restored landscapes in 2015, there was increased growing of tree tomatoes, which was mainly due to

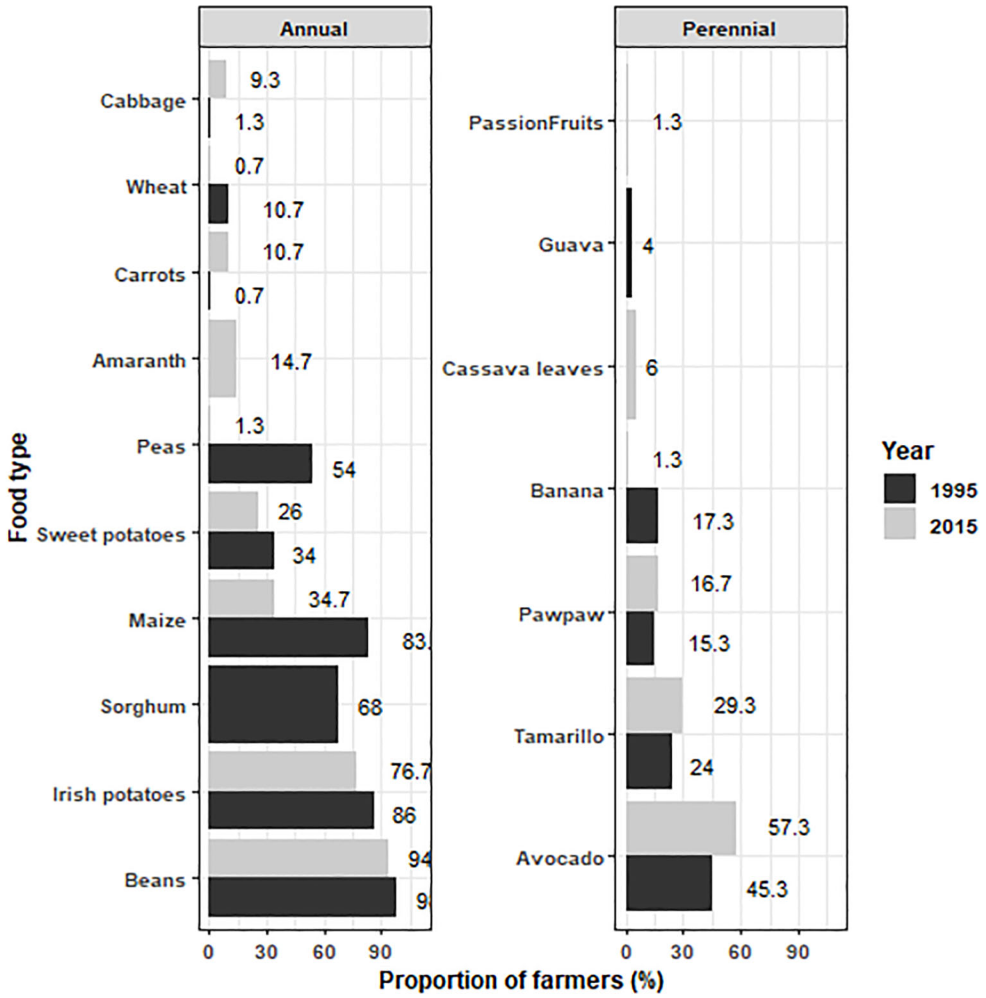

FIGURE 3
Proportion (%) of farmers growing crops in 1995 and 2015.

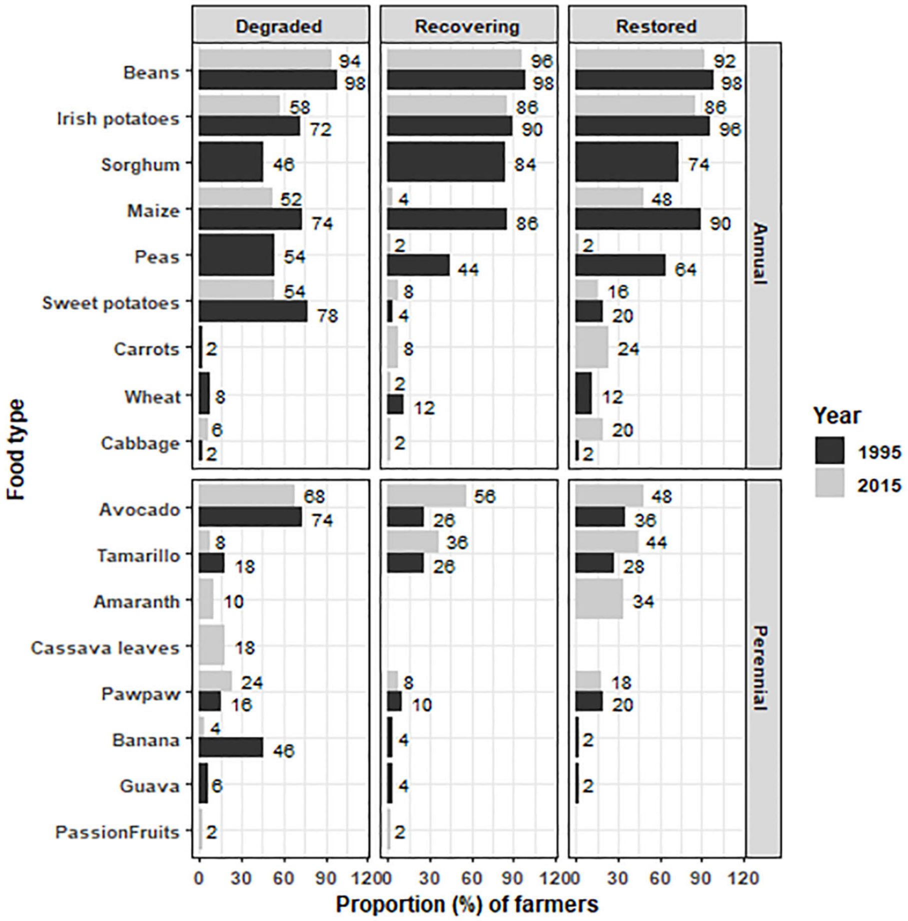

FIGURE 4
Proportion (%) of farmers growing crops in 1995 and 2015 by degradation level.

distribution of quality germplasm by projects such as the Trees for Food Security project through the World Agroforestry Centre (ICRAF).

3.2 Farmers' knowledge of drivers influencing crop diversity

Farmers identified six drivers influencing annual crop diversity, which occurred across four scales (regional, national, landscape and farm level) and of which four drivers varied significantly with land degradation status. The drivers were: at the national level (policies on crop intensification and eviction of farmers from Gishwati encroachment), at the regional level (climate change), farm level (land shortage and abandonment of slow maturing crops); and at the landscape scale (crop diseases).

According to majority of farmers (76%), the main driver that contributed to the decrease in annual crop diversity between 1995 and 2015 was the introduction of the Land-use Consolidation and Crop Intensification Program (CIP) that was launched in September 2007 as a policy by the Government of Rwanda. The program aimed at promoting the cultivation of three high value crops namely Irish potatoes, beans and maize, which fetched high income which the government believed would improve farmers' livelihoods significantly. Farmers however felt that specialization of a few high value crops has led them to abandon other crops they were growing, which were viewed as 'low value', thus resulting in decreasing diversity of such crops across farms. There were significant differences (p=0.05) in the number of farmers who mentioned CIP program by degradation status, with the driver being mostly mentioned by a significantly higher number of farmers in the Restored landscapes (88%) and Recovering landscapes (78%), compared to Degraded landscape (62%) (Figure 5).

Land shortage was the second most frequently mentioned driver of decreasing annual crop diversity (55% of farmers of all farmers). This was mainly blamed on the natural population increase among households, that led to sub-division of land amongst the kin. There were significant differences (p=0.001) in the number of farmers who mentioned land shortage, with fewer farmers in the recovering landscape mentioning this driver, significantly different from the other landscapes. Thirdly, 49% farmers reported having gradually abandoned slow growing and maturing crops such as sorghum and banana for fast-growing crops such as maize and Irish potatoes. There were significant differences (p=0.05) in the number of farmers

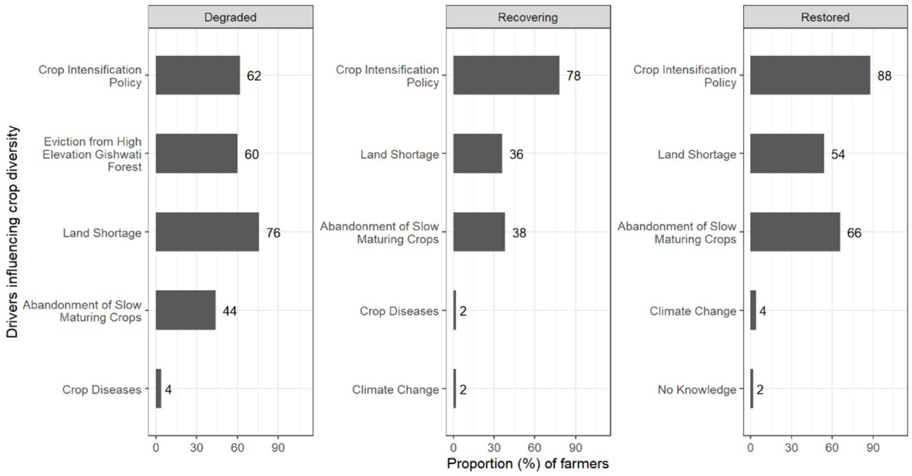

FIGURE 5
Drivers influencing annual crop diversity between 1995 and 2015 by degradation level.

who mentioned this driver, with it being mostly mentioned in the Restored landscape (66%) compared to degraded landscape (44%) and recovering landscape (38%).

The fourth driver, which was only reported by farmers in the degraded landscape by 60% of farmers (significant at p=0.001) was the eviction of farmers from Gishwati forest as the landscape is directly adjacent to the protected forest. When farmers were evicted from Gishwati forest which sits at a high elevation of above 2400 meters above sea level (m.a.s.l). where they were cultivating crops such as wheat and peas that do well in high elevation, they abandoned growing such crops when they were relocated to the low-lying areas of below 2000 m.a.s.l. which are unfavorable for growing such crops. Crop diseases and climate change drivers were mentioned negligibly by farmers across all landscapes.

Farmers identified two main drivers affecting perennial crop diversity, namely the increase in availability of tree seedlings (66%); and training of farmers on tree management practices, especially propagation methods including grafting of fruits such as avocadoes (34%). In the Recovering and Restored landscapes, there was increased in the number of farmers growing of tree tomatoes, which was mainly due to distribution of training and distribution of high-quality germplasm attributed to interventions such as by the Trees for Food Security project.

3.3 Relationship between crop diversity and food security

A total of 83% of farmers reported being food insecure, 96% and 86% of farmers from the degraded and restored landscapes respectively perceived themselves as being food insecure, significantly different (p=0.05); compared to 68% of farmers from the recovering landscape. Farmers identified four local indicators they use to assess their food insecurity status namely food shortage during certain months of the year, taking fewer meals per day throughout the year, consuming less preferred food and reducing food portions per meal.

The main indicator farmers use to assess whether they are food insecure as mentioned by 51% of farmers was food shortage during certain months of the year (mainly July to November), attributed to the depletion of food reserves during this five-month period when the three major crops (maize, Irish potatoes, beans) which farmers highly depend on are growing and not yet mature for consumption (Table 1). These dominant annual crops (beans, Irish potatoes, maize) are harvested and available for consumption only between December to February/March and from June to August. Due to a slightly different cropping calendar and variation of some food types grown, food-insecure months in the Degraded landscapes were from March to May and August to November while in the Recovering and Restored landscapes were from March to June and September to November. Perennial crops mainly tree crops such as avocadoes and tree tomatoes and cassava leaves were mostly available from June to February, and farmers reported relying on them to fill the food gap during the period when annual crops were not available.

The second overall most frequently mentioned indicator of food insecurity was farmers resulting to taking fewer meals per day throughout the year (47%). Farmers and their dependents resulted to taking one or two meals (most important meals) instead of the usual three throughout the year, without reducing food serving proportions per meal. According to farmers, the most important meal is dinner, followed by breakfast and lastly lunch. This coping strategy ensured that food reserves were utilized sparingly to last longer.

The third most frequently mentioned indicator (22%) was when farmers resulted to consuming less preferred foods such as sweet potatoes, cassava leaves and bananas, when the preferred foods such as Irish potatoes, beans and maize were not available. The fourth indicator was reducing food portions per meal (15%). This was achieved through taking three meals in a day but reducing serving portions to ensure little food is consumed.

There were significant differences in the number of farmers mentioning all indicators of food insecurity by land degradation status (Figure 6). Reducing food portions per meal was mainly

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TABLE 1 Annual and perennial food crop availability calendar.

	Botanical Name	Food Type	Main Rainy Season			Dry Season			Lighter Rainy Season			Dry Season		
			Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb
Degraded Landscape														
Annual Crops	*Phaseolus vulgaris L.*	Beans												
	Solanum tuberosum L.	Irish potatoes												
	Zea mays L.	Maize												
	Brassica oleracea var. *capitata*	Cabbage												
	Daucus carota subsp. Sativus	Carrots												
	Amaranthus spp.	Amaranth												
	Ipomoea batatas	Sweet potatoes												
Perennial Crops	*Carica papaya*	Pawpaw												
	Musa spp.	Banana												
	Cyphomandra betacea	Tamarillo												
	Psidium guajava	Guava												
	Persea americana	Avocadoes												
	Passiflora edulis	Passion fruits												
	Manihot glaziovii	Cassava leaves												
Recovering and Restored Landscapes														
Annual Crops	*Solanum tuberosum L.*	Irish potatoes												
	Zea mays L.	Maize												
	Pisum sativum	Peas												
	Brassica oleracea var. *capitata*	Cabbage												
	Daucus carota subsp. Sativus	Carrots												
	Phaseolus vulgaris L.	Beans												
	Amaranthus spp.	Amaranth												
	Triticum aestivum	Wheat												
	Ipomoea batatas	Sweet potatoes												
Perennial Crops	*Psidium guajava*	Guava												
	Carica papaya	Pawpaw												
	Cyphomandra betacea	Tamarillo												

(Continued)

TABLE 1 Continued

	Botanical Name	Food Type	Main Rainy Season			Dry Season			Lighter Rainy Season			Dry Season		
			Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb
Recovering and Restored Landscapes														
	Persea americana	Avocadoes												
	Passiflora edulis	Passion fruits												

Different colors are used to distinguish between annual and perennial crops.

mentioned in the Degraded landscape, varying significantly (p=0.001) from other landscapes. The other three indicators varied significantly among landscapes (p=0.05); with the main indicator mentioned in the Recovering landscape being food shortage during certain months (64%) and taking fewer meals per day throughout the year (62%); while consuming less preferred food was mostly mentioned in the Restored landscape (34%). On the other hand, in the Degraded landscape, all four indicators were mentioned by almost similar proportions of farmers.

3.4 On-farm and off-farm food sourcing trends between 1995 and 2015

We also sought to understand whether over time, farmers have become increasingly dependent on off-farm compared to on-farm food sourcing to meet their food needs. Farmers reported that due to decreased crop diversity discussed in earlier sections which led to them experiencing food insecurity, they had resulted to outsourcing food from off-farm sources, mainly buying from the market. As illustrated in Table 2, majority of farmers had become more dependent off-farm sources such as on the market, with food produced on-farm supporting farmers for average 6.6 months annually in 2015 compared to 10.1 months in 1995.

In 1995, more farmers from the recovering landscape relied more on on-farm and less on off-farm food sources in both year periods. Conversely, more farmers from the degraded landscape relied more on off-farm and less on on-farm food sources in both year periods. In 2015, there were variations, though not significantly different, in on-farm and off-farm food sourcing along a land degradation gradient, with farmers in the Recovering landscapes depending on their farms slightly more (7.8 months) in 2015 compared to the Restored (6.3 months) and Degraded landscape (5.7 months).

Figure 7 shows that in 2015, majority of farmers outsourced from the market and consumed eight out of the nine annual food crops they grew on their farms to supplement the food demand and outsourced 11 perennial crops though they only grew six. For annual crops, apart from beans that were grown by majority of farmers, farmers depended on off-farm sources for majority of other foods they consumed, significantly differing from on-farm sources. The food sourcing (growing and consumption) differences were especially apparent in the recovering landscape.

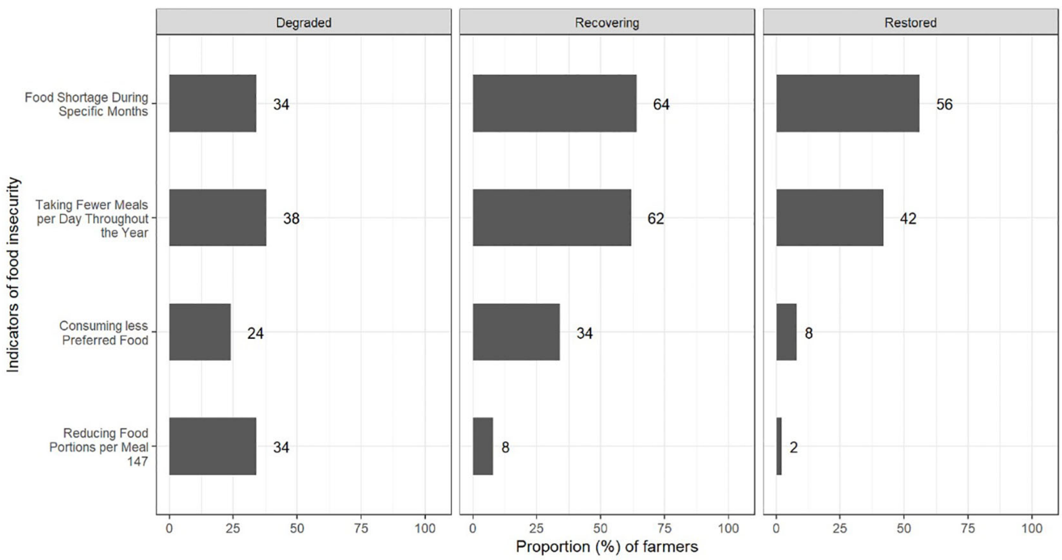

FIGURE 6
Local indicators of food insecurity by land degradation status.

TABLE 2 Comparison of 1995 and 2015 food sourcing proportion (months per year).

Food source	On-farm		Buy from market		Buy from neighbors		Borrow from relatives	
No. of months	1995	2015	1995	2015	1995	2015	1995	2015
All landscapes	10.1	6.6	1.5	5.4	0.1	0	0	0.01
Degraded	8.8	5.7	2.4	6.2	0.2	0	0	0.04
Recovering	11.4	7.8	0.6	4.2	0	0	0	0
Restored	9.9	6.3	1.5	5.7	0	0	0	0

4 Discussion

4.1 The role of local knowledge in promoting agroecological principles towards sustainable food systems

This study aims to revisit and validate findings of local knowledge data collected in 2015 in line with current literature to assess and understand changes, trends, and developments over time; and will provide continuity in understanding long-term intervention impacts of interventions. Findings from the current local knowledge study has brought out in depth understanding of seven out of the 13 agroecological principles that should guide food systems towards transitioning to becoming sustainable towards achieving sustainable food systems through enhanced crop diversity. The following subsections discusses each of the seven agroecological principles emerging from the results presented, which fall under two of the three operational principles on sustainable food systems (HLPE, 2019). Four principles fall under the strengthening resilience operational category namely: soil health, biodiversity, synergy and economic diversification; while three fall under secure social equity namely: social values and diets,

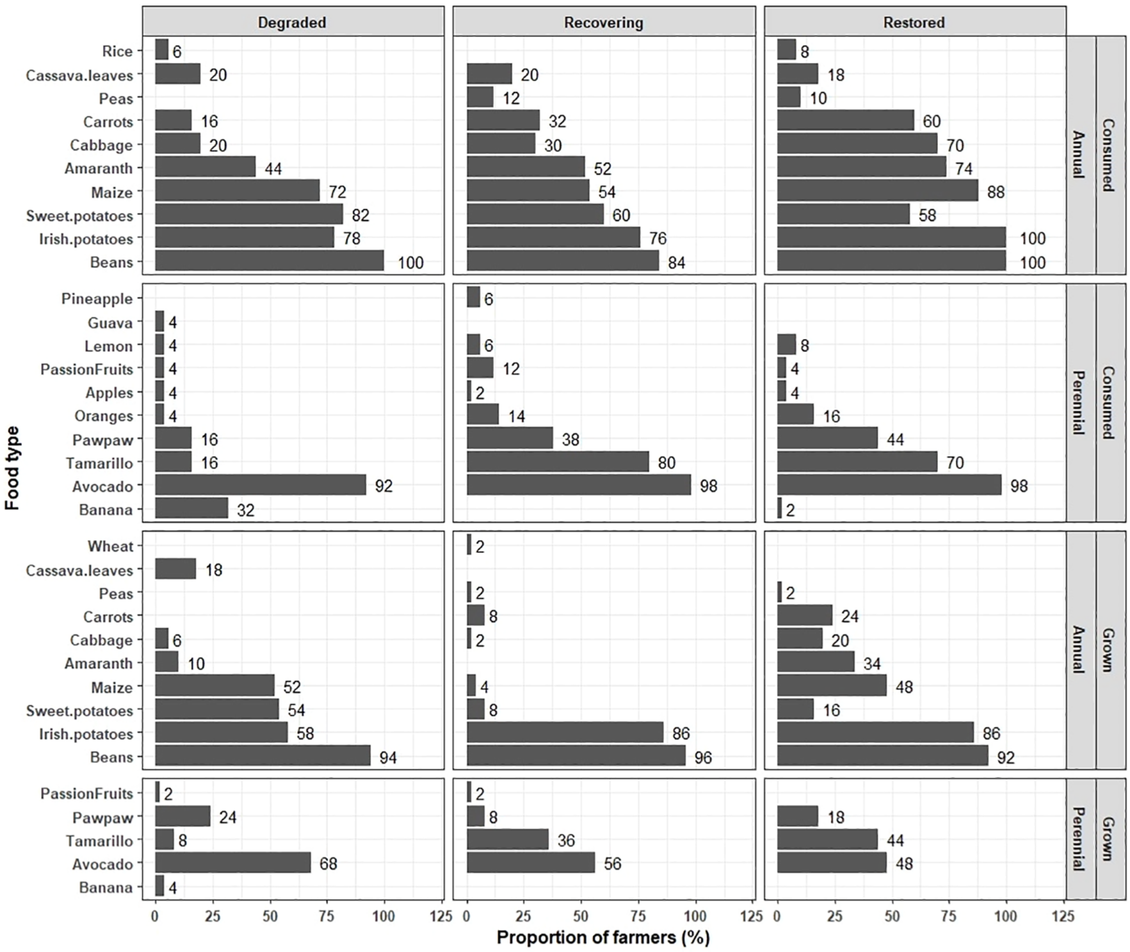

FIGURE 7
Proportion (%) of farmers who sourced food on-farm and off-farm in 2015.

co-creation of knowledge and participation. However, no agroecological principle was reported in relation to the role of crop diversity in improving resource efficiency, contrary to other studies that have highlighted this as a critical role (Chittapur, 2017; Isbell et al., 2017).

4.1.1 Soil health

Results showed significant differences in farmer's knowledge of various food security aspects namely crop diversity, food availability trends; drivers influencing food crop diversity and indicators of food insecurity across the three landscapes sampled along a land degradation gradient (degraded, recovering and restored systems). For example, results indicated lower percentage of farmers growing crops that have higher nutrient requirements (fertile soils) such as Irish potatoes and maize in the degraded landscapes. In a previous study in the same landscapes, land degradation was found to influence soil quality as soils in the degraded landscape were found to have lower organic matter and lower diversity of beneficial macrofauna species hence less productive compared to recovering and restored landscapes (Kuria et al., 2019). Studies have shown that crops that have higher nutrient requirements are often not adapted to low-input systems and can only be grown successfully in degraded and less fertile land through involving a high-input farming system that relies heavily on external inputs such as fertilizers (Bucagu et al., 2020; Mugendi, 2013). Heavy reliance on external inputs further leads to decreased soil health and quality through pollution (Singh et al., 2023). Results further indicate that land shortage was the main driver of low crop diversity in the degraded landscape as mentioned by 76% of farmers. Studies show that increased population leads to land fragmentation and decreased average household land sizes. This results into adoption of intensified farming practices such as continuous cultivation without fallows; and specializing on high income monocrops in order to maximize on returns on land (Jiang et al., 2021). This in return has negative effects on soil health due to soil fertility depletion.

These results demonstrate the need for Rwandan government and other food policy actors to adopt agroecological practices that promote integrated soil management practices including structural practices that control soil erosion, biological and cultural practices (Garrity et al., 2010; Mutemi et al., 2017); including practices that restore soil health in the long-term mainly aimed at increasing soil organic matter and the introduction of shrubs and crops that improve soil fertility on the degraded systems such as the nitrogen-fixing leguminous crops (Bolo et al., 2024; Yao et al., 2023). Gradually, once degraded soil is restored, farmers can then be able to diversify their systems through growing crops that have high nutrient intake such as maize and Irish potatoes in such landscapes.

4.1.2 Biodiversity

Results in Figure 3 and Figure 4 show that on farm annual crop diversity decreased between 1995 and 2015, with some crops such as sorghum, peas and wheat disappearing from farms; while only a few crops were prioritized mainly Irish potatoes, beans and maize blamed on the Crop Intensification Program (76%), land shortage (55%) and abandonment of slow growing crops (49%). Despite the interventions of the crop intensification Program, which was highly heralded as an example of the 'new' Green Revolution (Cioffo et al., 2016) leading to an increased yields for these priority crops, the program has also led to decreasing annual crop diversity (Seburanga, 2013) due to promotion and intensification of only a few crops while other crops viewed as of 'low value' are ignored.

Local knowledge acquisition highlighted the importance of promoting and maintaining biodiversity; and led to the realization of the negative impacts of decreasing annual crop species diversity in space and time (between1995 and 2015) such as food insecurity during certain months that priority crops were still growing and not ready for consumption. Studies show that gradual specialization in few crops results into the farming systems becoming more simplified and less resilient (Altieri and Nicholls, 2020). This is because monocultures lead to the gradual agricultural biodiversity loss and increase vulnerability of a system to adverse threats such as climatic variabilities, pests and diseases (Barthel et al., 2013; Luedeling et al., 2014).

Further, the specialization on a few exotic perennial crops at the expense of native perennials has been blamed on the loss of on-farm diversity in Rwanda (Ruticumugambi et al., 2024). Still, recent studies which revisited Rwanda's crop intensification program further noted that specialization in the few priority crops overlooks the heterogeneity and dynamic nature of Rwandese farmers' social, economic and environmental context (Franke et al., 2019; Kim et al., 2022). This has resulted in inequalities in benefits generated from the CIP program.

4.1.3 Synergy

Results from the cropping calendar indicated synergies and complementarity brought about by the integration of perennial crops, in this case trees and annual crops in achieving food security all year round. This is because different tree species play unique roles in the system, both through provisioning ecosystem services or ecologically and products mature at different periods of the year (Carsan et al., 2014). For example, having more fruit tree species, whose fruiting phenology is varying means that fruits are available in different months of the year, hence continued access to products and income, which supplement annual food crop sources.

Increasing crop diversity (annual and perennial) is especially critical and beneficial in restoring degraded lands because it not only demonstrate the role that individual crops play towards enhancing food security throughout the year, but enhances the functional diversity roles played by various crops collectively such as nutrient cycling, erosion control, and ecosystem products (Di Falco and Chavas, 2009). For example, farmers in Rwanda reported achieving higher yields of potatoes, maize, and beans on farms with trees in the humid region, and higher yields of beans in the semi-arid regions (Cyamweshi et al., 2023). Further, expanding crop portfolios is viewed as an ecological adaptation to climate change and enhanced resilience from diseases (Meldrum et al., 2018). A recent study in Rwanda (Hashakimana et al., 2023) has further revealed that high carbon sequestration and subsequently high soil organic carbon was found among mixed-cropping systems compared to the CIP monocropping systems. By elevating the multifunctionality of systems, crop polycultures can achieve greater functional diversity (Finney and Kaye, 2017). Dusingizimana et al. (2024) further notes that dietary diversity in Rwanda in the recent years has been enhanced through integrating livestock within cropping systems. The interaction of components in both space and time results in numerous advantages and synergies for stakeholders across a wide spectrum of products and services. This therefore promotes complementarities through promoting the production of multiple ecological products and services simultaneously (Matsushita et al., 2016).

4.1.4 Economic diversification

While the government of Rwanda introduced CIP with the aim of achieving economic growth, food security and livelihood development (Kim et al., 2022) but which results show led to reduced crop diversity on the contrary. Farm diversification through crop diversification has been found to contribute towards livelihood resilience by enhancing farm productivity by providing additional income and nutritional diversity generated through off-farm sourcing (Makate et al., 2016; Nsabimana et al., 2021). In addition, including different crops in a farming system acts as a type of natural insurance against unfavorable markets, drought; pests and diseases (Benin et al., 2004). Hence farmers can still benefit from and rely on some crops when other crops in their systems fail. On the other hand, specialization in a few crops by the same population has been reported to cause low economic returns due to market competition (Byerlee et al., 2014). Miklyaev et al. (2021) calls for the need for Rwanda government to respond to market demands while designing future crop intensification programs Further, having different annual and perennial crops maturing at different times of the year leads to diversified income streams as farmers can sell their farm produce throughout. (Niether et al., 2020) found the total system yields for mixed agroforestry systems to be ten times higher than monocrops, contributing to food security and diversified income.

4.1.5 Co-creation of knowledge

Results of this study demonstrated that smallholder farmers have detailed and explanatory knowledge about crop diversity and the role it plays towards meeting their food security and livelihood needs. They were able to describe drivers that have influenced their annual and perennial crop diversity, cropping calendars including the role perennial crops play in their agricultural systems; and indicators of food insecurity. Interviewing farmers across different land degradation status further brought about heterogeneity of context. Such knowledge would be critical in complementing the already available scientific knowledge of the area through providing in-depth understanding about the complexity and heterogeneity of the Western Rwanda agroecological systems (Sinclair et al., 2019; Wezel et al., 2020); and hence would guide food policy makers to customize interventions to the context (Rossing et al., 2021).

Local knowledge itself falls under the co-creation of knowledge agroecological principle and plays a key role in the development of locally adapted practices; and was the over-arching agroecological principle guiding this study. Local knowledge is inherently context-specific, shaped by socio-ecological interactions and passed through generations (Berkes, 2009). Unlike scientific knowledge, which often seeks universal principles, local knowledge is adaptive and dynamic, making its validation a complex process that extends beyond mere comparison with scientific findings (Agrawal, 1995). Our study applied a co-creation approach that integrates scientific and local knowledge through an iterative process of elicitation, interpretation, and validation with farmers (Chambers, 2007; Fuchs et al., 2023; Kuria et al., 2024). This approach aligns with growing recognition that knowledge pluralism, where multiple ways of knowing are equally valued enhances agricultural innovation and policy relevance (Turnhout et al., 2019).

Due to the heterogeneity of smallholder farming systems, policy makers should ensure that they design food security policies informed by the local context (Coe et al., 2014). This should begin with gaining local understanding and knowledge of which measures are appropriate in each context including not only direct measures such as structural changes but indirect policy measures such as improving agricultural infrastructure, understanding the biophysical and socioeconomic, and providing farmers with new farm technologies (Berazneva and Lee, 2013). Also of importance is adapting food programs to dynamic local indicators such as climate change, soil conditions and land degradation (Kuria et al., 2019, 2023) and where adaptation information is unavailable, policy makers should communicate such information to local communities (Thornton et al., 2018).

Agroecology is based on bottom-up and territorial processes, helping to deliver contextualized solutions to local problems and hence it depends on local contexts, constraints and opportunities. This calls for the need to adapt food systems to the current context and viewing farmers as co-innovators of knowledge rather than passive adopters of technologies. It is important to collectively find innovative ways of increasing the transformational resilience and adaptive capabilities of smallholder farmers (Savage et al., 2020). This will result into co-learning and co-creation of new knowledge (Frias-Navarro and Montoya-Restrepo, 2020; Marinus et al., 2021). There is therefore urgent need to rethink and formulate food policies that incorporate local food systems rather than that are top-down and not informed by what works locally (Galimberti et al., 2020).

The findings of this study contribute to the growing discourse on local knowledge and knowledge co-creation in agroecological transitions, aligning with and extending previous research. Similar to Tolinggi et al. (2023), who explored knowledge transfer across generations, this study revealed that farmers in Gishwati rely on intergenerational knowledge to navigate the crop diversity–food security–land degradation nexus. However, while Tolinggi et al. (2023) emphasize how traditional farming wisdom is passed down, the current study highlights the disruptions caused by external policies, such as Rwanda's Crop Intensification Program, which has influenced knowledge retention and adaptation processes. Moreover, Arifah et al. (2023) examined knowledge co-creation in response to climate change, emphasizing the importance of integrating scientific and local knowledge for adaptive decision-making. Our findings similarly underscore the role of farmers' experiential knowledge in shaping agroecological practices, particularly in relation to crop diversity and resilience strategies. However, while Arifah et al. (2023) focus on farmer–scientist collaboration, this study revealed a gap in structured co-creation mechanisms, with farmers primarily relying on informal knowledge networks rather than institutionalized participatory platforms.

Additionally, Arham et al. (2024) investigated knowledge construction among coffee farmers, highlighting the role of collective learning in improving productivity and sustainability. Our study complements this perspective by demonstrating how knowledge co-creation extends beyond productivity concerns to encompass broader agroecological principles, such as biodiversity conservation and food security. While both studies emphasize the significance of shared learning, our findings suggest that knowledge fragmentation due to shifting policy priorities can hinder the continuity of local knowledge systems.

Furthermore, local knowledge systems are shaped by ecological, socio-economic, and gendered factors, influencing the adoption of agroecological practices. Women and men contribute distinct expertise, women often manage seed selection and intercropping for resilience, while men focus on land preparation and cash crops (Bezner Kerr et al., 2019; Meinzen-Dick et al., 2019). Recognizing these gendered roles is essential for developing sustainable, locally adapted solutions (Ramirez-Santos et al., 2023). Policies that overlook gendered knowledge risk reinforcing inequalities. Inclusive, participatory approaches are crucial for co-creating knowledge and designing equitable contexts (Nyantakyi-Frimpong et al., 2017).

4.1.6 Social values and diets

Results indicate that 83% of farmers reported being food insecure. Results from the seasonal calendar presented in Table 1 indicated that households that had higher crop diversity including perennials such as fruits were more food secure, especially during food gaps when annual crops are unavailable. This was the main indicators of food insecurity reported by farmers whereby July to November were named as the most food insecure months. Seasonal food shortage has been reported to result to poor maternal and child health due to hunger and deprivation of micronutrients critical for growth (Belayneh et al., 2020; Fraval et al., 2020; Waswa et al., 2021). Adjimoti and Kwadzo (2018) further observes that increased crop diversity in Benin ensured that different crops are available for consumption throughout the year, hence fulfilling the accessibility pillar of food security. This was also echoed in Rwanda by (Ndoli et al., 2021), where on-farm trees were found to act as a safety net for many smallholder households, with food insecure households relying more on income from sale of trees to meet their food needs. Studies indicate a positive co-relation between tree cover and dietary diversity because of availability of fruits and vegetables provided by trees (Ickowitz et al., 2014; McMullin et al., 2019). Agroforestry trees provide nutrient-rich foods that contribute towards improved dietary diversity of women and children (Lourme-Ruiz et al., 2021).

Taking fewer meals per day throughout the year, consuming less preferred foods and reducing food portions per meal were also reported as indicators of food insecurity (Figure 6). Decreasing crop diversity also results into nutritional insecurity as households who traditionally enjoyed a wide diversity of nutritious crops become confined to consuming foods only a few food crops throughout the year, which may have low nutritional and dietary value hence may lead to poor health (Burchi and De Muro, 2016). Low dietary diversity, malnutrition and micronutrient deficiencies have been widely reported among Rwandese women and children (Sly et al., 2023; Xavier et al., 2024). Consuming less preferred food was also reported elsewhere in Peru and Ethiopia (Ambikapathi et al., 2018; Dessalegn, 2018). Globally, low crop diversity has been linked to reduced nutritional stability, as it often results in a focus on crops with fewer nutrients or nutrients already abundant in the existing food system (Nicholson et al., 2021). These findings go on to show that food insecurity manifests in different ways in different context, and communities cope in different ways, hence the need to develop food policies and programs that are informed by the different food insecurity indicators.

The abandonment of slow maturing crops such as sorghum and bananas was also reported as a driver of decreasing crop diversity. This has not been widely reported in literature. In Rwanda, decreased crop diversity especially loss of indigenous crops has instead been attributed to cultural heritage erosion and disintegration due to colonization and introduction of alien crops (Seburanga, 2013). Rwibasira (2016) further notes that promoting high-value crops through CIP in Rwanda, a country where men dominate economic fronts, has led to alienation of women from crop production activities. Such form of skewed intensification has been reported in other countries including in Ethiopia (Shiferaw et al., 2014); and contributes towards gender inequalities in food production systems. Similar patterns have been documented in Mali, aligning with the paradox of Sikasso, where agricultural intensification does not necessarily translate into improved gender equity (Dury and Bocoum, 2012).

4.1.7 Participation

Farmers attributed Crop Intensification Program (CIP), one of the major agricultural reforms initiated in 2007 by the Rwandan government as the main cause of decreasing annual crop diversity. The main goals of the program were to increase agricultural productivity in high-potential food crops (maize, wheat, rice, Irish potato, beans and cassava) and ensuring food security and self-sufficiency across the entire country (Muhinda and Dusengemungu, 2011). Despite the Rwandan government putting in place this food security policy, various authors have noted the lack participation of farmers at the design and operational stages of policies including monitoring of such policies (Namugumya et al., 2020; Welteji et al., 2017). Strengthened collaboration among farmers, local leaders, extension agents, and agricultural service providers, combined with the practical skills of farmers will significantly enhance participation in the CIP program in the future (Nahayo et al., 2017; Sunday et al., 2024). Using local community's feedback could play a key role in adapting such policies (Moroda et al., 2018). Agroecology represents an approach that is transdisciplinary, participatory, and oriented toward practical action (Méndez et al., 2013; Sinclair et al., 2019). Participation advocates for the involvement of a transdisciplinary team of experts to address the various dimensions of food systems through inclusion of stakeholders and integrating knowledge systems at multiple levels to develop food security innovations that are suited to local context.

Food insecurity and severity is dependent on factors such as gender. For example, in Kenya, Uganda and Tanzania (Silvestri et al. (2015) found that female headed households were more food secure compared to male headed households because women focused on more diverse crops that are not necessarily income oriented compared to men. Participation therefore calls for inclusion whereby all gender are involved due to the unique roles they play in food production, possess unique knowledge, preferences and risk-taking behaviors (Villamor et al., 2014). Sariyev et al. (2021) further observes that participation of all gender leads in inclusive decision making resulting in higher diversity of produced and consumed food.

The link between crop diversity and food security is well-documented, particularly in relation to women's roles in subsistence farming and household nutrition. In the studied landscapes, the shift towards high-value cash crops under the CIP program may have disproportionately affected women's ability to maintain dietary diversity within households. Traditional crops, many of which were rich in essential nutrients, were replaced by market-oriented staple crops, potentially altering household food consumption patterns. While men are involved in high-value, market-oriented crops (Ingabire et al., 2018); women, who are typically responsible for food preparation and household-level food sourcing, likely faced greater challenges in maintaining diverse and balanced diets. Additionally, land shortage and the abandonment of slow-maturing crops both identified as key drivers also had gendered implications. Women often cultivate small, intercropped and diversified plots to ensure food security (Nakazi et al., 2017), but the declining availability of land may have reduced their ability to maintain diverse home gardens.

On-farm perennial crop diversity was found to be increasing between 1995 and 2015, with the main drivers being increased access to quality germplasm of preferred agroforestry tree species and farmers acquiring tree propagation skills. This is mainly attributed to the introduction of participatory approaches (Iiyama et al., 2018; Ndoli et al., 2021) that saw a move from the historical top-down seed and seedling sourcing, to a system where farmers are involved in tree species selection and have access to high quality tree germplasm and are continuously trained on tree propagation and management through ongoing initiatives namely the Trees for Food Security project, which the World Agroforestry Centre was leading at the time this study was undertaken.

4.2 Beyond the farm: implications of off-farm food sourcing on agroecological transitions

Results in Table 2 indicated that over time, farmers have become more dependent on sourcing food from outside their farms, with food produced on-farm supporting farmers for an average of 6.6 months annually in 2015 compared to 10.1 months in 1995. In 2015, farmers in the degraded landscape were more dependent on off-farm food sources (an average of 6.2 months) annually compared to those in a recovering landscape (4.2 months) and a restored landscape (5.7 months). Further, Figure 6 shows that in 2015, majority of farmers outsourced from the market eight out of the nine annual food crops they grew and outsourced 11 perennial crops though they only grew six. This trend is an indication that farmers in Gishwati were often lacking diversity of food crops to sustain their food and nutritional needs. Similar trends of food insecure households relying on off-farm food sourcing such as buying food from the market has been reported (Ali et al., 2014; Fraval et al., 2020).

However, while the Crop Intensification Program (CIP) has played a central role in shaping land use and crop diversity, it is not the sole driver of market dependency and reduced on-farm food provisioning. The increasing monetization of rural economies in sub-Sahara Africa, driven by economic liberalization, globalization, and national policies, has accelerated reliance on off-farm food sources and commercial production. As highlighted in our discussion, this transition aligns with broader trends reported in the literature, where structural shifts in rural economies have contributed to declining crop diversity and heightened food security challenges (Fraval et al., 2019). Recognizing these external pressures is crucial for designing agroecological policies that balance market participation with localized, resilient food systems.

Unlike India's Public Distribution System (PDS), which provides subsidized food grains to vulnerable populations (Kumar, 2021; Pingali et al., 2019), Rwanda's policies have focused on agricultural intensification, particularly through the Crop Intensification Program (CIP), which promoted high-value staple crops but reduced on-farm diversity and increased market dependency (Van de Poel et al., 2014). On-farm food provisioning declined from an average of 10.1 months per year in 1995 to 6.6 months in 2015, with degraded landscapes experiencing the highest reliance on market purchases. While government initiatives like the 'One cow per poor family '*Girinka*' program have improved nutrition and income for some households, they do not offset the vulnerability caused by reduced crop diversity and fluctuating food prices (Fanzo et al., 2020). Additionally, food sourcing strategies varied by landscape degradation status, with farmers in Recovering landscapes maintaining slightly higher on-farm food reliance than those in Degraded landscapes, underscoring the need for targeted interventions to enhance food security in highly degraded areas.

Some studies, however, found that relying on off-farm food sources and income may have a positive effect on food security and nutritional diversity through providing alternative sources of food

(Aboaba et al., 2020; Sibhatu and Qaim, 2018). This is especially so when there are inevitable threats and uncertainties such as extremely poor and unproductive soils, climate change vulnerabilities in areas where populations depend on rain-fed agriculture or due to total crop failure resulting from pests and diseases (Babatunde and Qaim, 2010; Owusu et al., 2011). These findings underscore the potential of combining market-based strategies with on-farm crop diversification to support food security objectives (Morrissey et al., 2024; Ume et al., 2023). However, although this food insecurity coping behavior provides immediate and temporary quick-fix solution, it leads to undesired outcomes in the long run as this behavior takes farmers away from investing in improving their farms (Bouahom et al., 2004) such as adopting agroecological practices that would make them productive and resilient in the long run.

Land shortage was reported as a major driver of food insecurity and influenced crop diversity, with the overall average household land size being 0.3ha while in the Degraded landscape the average land holding was 0.15 ha. This opens up a concern regarding the critical point at which land becomes too small to accommodate crop diversification and sustain food production let alone remain ecologically resilient (Henriksson et al., 2018; Mungai et al., 2016). This provides a huge opportunity for the implementation of agroecological principles on-farm to increase productivity while protecting the environment of such landscapes (Wezel et al., 2014).

Further, with increasing population pressure, this brings out another pertinent question regarding what complementary options are left for smallholders whose land is too small to produce enough food apart from relying on off-farm strategies. Therefore, this in return is a call to food policy makers to have a local understanding of sustainable and appropriate mechanisms to adapt to land limitations (Holden and Yohannes, 2002). This includes wholistic adoption of agroecological principles including looking beyond the farm and into the neighboring landscapes and using ecological boundaries and not administrative boundaries (Pagella and Sinclair, 2014). This will ensure that other agroecological principles such as connectivity will promote equitable and efficient distribution networks for food, while also reintegrating food systems into local economies; and putting in place mechanisms for fair trade for smallholder producers so that they benefit more significantly when purchasing food or selling their crop produce.

4.3 Promoting agroforestry adoption to enhance resilient and food secure systems

Results throughout have demonstrated the critical role that perennial crops such as agroforestry trees play a role in enhancing agroecological principles towards meeting food security needs within farming systems. Not only does having trees on farm become beneficial as trees provide numerous benefits through products such as fruits, vegetables, edible pulp, nuts; timber, fuel, fodder, and income (Jamnadass et al., 2011). Agroforestry also plays indirect roles that help to promote ecological processes that support food production. These include: soil erosion control, soil nutrient cycling, pollination regulation, microclimate regulation, carbon sequestration and ground water recharge (Mbow et al., 2014; Minang et al., 2014; Muthuri et al., 2009). Integration of trees within farming systems therefore contributes to food security, poverty eradication and promotes livelihood and ecological resilience including climate change mitigation and adaptation (Wakaba et al., 2025). Ecological and livelihood benefits of trees are increased when there is not only higher tree diversity but also density on farms (Iiyama et al., 2017; Magaju et al., 2020).

However, in order to realize and optimize the role of agroforestry in enhancing food security, more needs to be done to address the current challenges being faced in adoption and scaling of agroforestry technologies. Studies have shown that effective scaling of agroforestry technologies in sub-Sahara Africa has been limited by various factors such as: lack of farmer participation and involvement throughout project phases from the design stage, lack of quality germplasm, and lack of tree management skills (Franzel et al., 2002; Kabwe et al., 2009). Other factors include: the inability of farmers to see tangible benefits of interventions which leads to low adoption and lack of access to markets (Bayala et al., 2010; Kiptot et al., 2007). Through initiatives from various organizations including the World Agroforestry Center (ICRAF) through the Trees for Food Security Project, these challenges are being addressed. For example, there is a move from the conventional promotion of only a few tree species were being promoted through a top-down seed and seedling systems in Rwanda. Through participatory research approaches, farmers are now being involved in selection of diverse and inclusive tree species that suit their landscapes and needs (Dumont et al., 2017). Farmers are also provided with quality germplasm and equipped with propagation skills that promotes scaling of agroforestry across the landscapes. This is supported by Figures 3 and 4, which showed an increasing number of farmers planting tree crops in 2015 compared to 1995, attributed to access to quality germplasm (66%) and the training and skills they have received from the project on tree propagation, including grafting of fruit trees (34%).

Further, results showed that soil loss through erosion was mainly reported in the Degraded landscape where unlike other landscapes, farmers reported working individually (Kuria et al., 2019. Scaling of agroforestry requires a move from working individually at the farm/field level to working collectively at the landscape scale and beyond and working with multiple stakeholders (Sinclair, 2017). This is especially for ecological benefits such as soil erosion control and ground water recharge (Thornton et al., 2018). When the above constraints are addressed, coupled with the favorable conditions such as sloped terrain, high rainfall and collective action, there is great potential to scale agroforestry to enhance food security, thereby generating context-relevant multiple ecosystem services in Gishwati and Western Rwanda region in general.

5 Conclusions

This study revealed a significant decline in annual crop diversity in Gishwati, Rwanda, between 1995 and 2015, with some crops disappearing entirely. Farmers identified three primary drivers: the government's Crop Intensification Program (76%), which prioritized high-value crops like Irish potatoes, maize, and beans; land shortages (55%); and the abandonment of slow-growing crops (49%). These factors led to the specialization in a few high-value crops, resulting in reduced crop diversity. Consequently, 83% of farmers reported food insecurity, with seasonal food shortages (July to November) as the most common indicator (51%), followed by fewer meals (47%), consuming less-preferred foods (22%), and reducing portion sizes (14%). Perennial crops, particularly fruit trees, played a critical role in bridging hunger gaps during food-insecure periods.

The study highlights the importance of increasing crop diversity by integrating annual and perennial crops, including those considered "low-value," to enhance food and nutritional security. Significant variations were observed in crop diversity, food availability trends, and food insecurity indicators across degraded, recovering, and restored landscapes, underscoring the need for context-specific interventions tailored to land degradation status. The research identified seven agroecological principles—biodiversity, synergy, economic diversification, social values and diets, soil health, and participation—that are critical for addressing the crop diversity–food security–land degradation nexus. Food produced on-farm sustained households for only 6.6 months in 2015, down from 10.1 months in 1995, increasing reliance on off-farm food sources. This reliance indicates systemic gaps, where short-term solutions hinder long-term investments in farming systems and sustainable food production. To address these challenges, holistic promotion of agroecological principles is essential. This includes leveraging ecological rather than administrative boundaries, ensuring connectivity within food systems, and fostering equitable trade mechanisms for smallholder farmers. The study also highlights opportunities to implement agroecological practices on small farms (average size 0.3 ha) to enhance productivity and environmental protection. However, it raises concerns about the minimum land size needed to sustain crop diversification and ecological resilience.

In conclusion, the study calls for food security policies to embrace both crop diversity alongside specialization and ensure the interventions are adapted to local contexts. Findings from this study have been validated and supported through numerous literature and studies over time. Therefore, incorporating co-creation of knowledge by integrating local and scientific knowledge into agroecological food policies can ensure context-appropriate, inclusive, and sustainable solutions, fostering resilience in smallholder farming systems and advancing transitions to sustainable food systems.

6 Limitations of the study

While this study offers critical insights into the agroecological transitions in Rwanda and the role of local knowledge in understanding the crop diversity–food security–land degradation nexus, it has several limitations:

1. Scope and Temporal Scale: The study relies on data spanning from 1995 to 2015. While this provides a long-term perspective, it does not capture recent developments, including recent policy changes and their impact on crop diversity and food security.
2. Geographical Coverage: This research focuses on Gishwati, Rwanda, as a case study, which may limit the generalizability of findings to other regions with different agroecological and policy contexts.
3. While local knowledge is a prerequisite for designing contextualized solutions for crop diversification–food security nexus, additional methodologies such as policy engagement to bridge the gap between local knowledge recognition and actionable policy recommendations.

To build on these findings, future research could focus on the following areas:

1. Expanding Longitudinal Studies: Extending the timeframe of analysis to include more recent data will help capture current agroecological trends and evaluate the long-term effectiveness of policy shifts.
2. Comparative Studies Across Agroecological Zones: Conducting comparative studies in different agroecological zones and policy environments would enhance understanding of how contextual factors influence agroecological transitions.
3. Future research could also focus on developing and testing participatory policy engagement frameworks that effectively integrate local knowledge into actionable policy recommendations. This could involve exploring co-creation processes between farmers, policymakers, and researchers to bridge the gap between local knowledge recognition and the formulation of policies that support crop diversification and food security.

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/YQJ0SH.

Ethics statement

The studies involving humans were approved by Bangor University 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, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. TP: Conceptualization, Investigation, Methodology, Supervision, Validation, Visualization, Writing – review & editing. CM: Conceptualization, Methodology, Project administration, Supervision, Validation, Writing – review & editing. FS: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing.

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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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