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An empirical analysis of the determinants of food insecurity among smallholder farmers in Eastern Rwanda

Hilda Kegode[1,2*], Selma Tuemumunu Karuaihe[1], Wegayehu Fitawek[1] and Damien Jourdain[1,3,4]

Abstract

Background Food insecurity is one of the most pressing problems confronting households in sub-Saharan Africa (SSA). It is particularly acute in low income areas across the continent. Despite Rwanda's economic progress, food insecurity persists especially in rural areas, necessitating empirical evidence to inform targeted interventions that address the complex interplay of socio-economic, environmental and policy factors affecting household food insecurity. Factors affecting food insecurity vary, and obtaining context-specific information is necessary for designing relevant interventions. This empirical study analyzes factors affecting the probability of experiencing severe food insecurity in Eastern Rwanda and discusses how land restoration strategies like agroforestry may contribute to it. Panel data collected in 2018 and 2022 from 1100 randomly selected households are analyzed using both descriptive statistics and a correlated random effects probit model.

Results The findings show a generally high level of food insecurity, with sample households having average food insecurity experience scale scores of 6.02 in 2018 and 5.73 in 2022. Moreover, 63% and 60% of the households experienced severe food insecurity in the two periods, respectively. The empirical results show that farming practices and household socio-economic characteristics played a more significant role in food insecurity status. Households that cultivated different crops had a lower probability of experiencing severe food insecurity and larger households were more likely to experience severe food insecurity. However, agroforestry-related variables were not statistically significant in reducing the probability of severe food insecurity experience in the study area.

Conclusion The study concludes that food insecurity in the study area is high. To address the prevailing situation, efforts to reduce food insecurity should focus on solutions that could increase food production in the short term, such as improving household socio-economic status, diversifying crop production and market-focused production. However, these need to be aligned with local needs and ecological conditions. Agroforestry interventions should focus on integrating suitable tree species into farming systems, and future studies should account for the time dimension to accurately capture long-term effects of such interventions. Moreover, experimental studies to enable rigorous impact analysis of agroforestry interventions are recommended.

*Correspondence:
Hilda Kegode
h.kegode@cifor-icraf.org; h.kegode@gmail.com
Full list of author information is available at the end of the article

Introduction

Food security is multidimensional consisting of different aspects including food availability, food accessibility, food utilization, and food stability [1–3]. According to the Food and Agriculture Organization (FAO), food security is achieved when all people have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for a healthy life [3]. A disruption in any of the dimensions may result in food insecurity [2]. Sustainable Development Goal number 2 (SDG 2) aims to end hunger in all its forms by 2030. However, reports show that this might not be achieved, particularly in sub-Saharan Africa (SSA), where at least one person out of five faced hunger in 2023, and more than 120 million people in Eastern Africa were severely food insecure in the same year [4].

At least 60% of households in SSA are smallholder farmers who own less than one hectare of land but produce most of the region's food [5–10]. However, these farmers are highly susceptible to food insecurity, mainly due to the subsistent nature of production and high levels of poverty [4, 11]. Food production is hampered by challenges such as land degradation, climate-related shocks and high post-harvest losses [5, 7, 11–14]. It is estimated that Africa's population will reach 2.5 billion people by 2050, significantly increasing food demand and requiring improvement in agricultural production [15, 16]. In Rwanda, food insecurity remains a challenge especially in rural areas. The country's population is expected to increase by 82% by 2050 [17], raising concerns about future food insecurity, especially for rural households [1, 14, 18, 19]. Farmers must therefore aim to strategically and optimally produce sufficient food on the available arable land [20, 21].

One strategy that has been championed to improve food security across SSA is agroforestry, the deliberate integration of multipurpose trees into farming systems [5, 16, 22–24]. Agroforestry has primarily been promoted for its soil enhancing properties and potential to improve people's livelihoods [16, 23, 25–27]. Agroforestry can increase household income generating streams, improve crop productivity; complement diets with fruits, seeds and nuts, and enhance climate change adaptation [13, 26–30]. By diversifying agricultural systems and enhancing ecosystem services, agroforestry contributes to the realization of SDG 2.4 which focuses on ensuring sustainable food systems [26]. The empirical evidence of the impact of agroforestry practices on household socio-economic outcomes including income and food security, however, remains scarce [14, 26, 31–35]. Previous studies vary with regard to the relationship between agroforestry and food security. In a study in India, Singh, Choudhary [36] found that increases in tree density and species diversity were associated with an improved food consumption score (FCS), because households consumed fruits from agroforestry trees, and earnings from tree products increased household income available to purchase other food items. In Malawi, Coulibaly, Chiputwa [27] showed that the adoption of fertilizer trees led to a significant improvement in maize productivity, resulting in higher food security for adopters. Ndoli, Mukuralinda [14] observed that food security was higher among high agroforestry practitioners in Rwanda, attributing this to a higher income from crops but with some limited contribution of tree income. However, a higher tree density did not always lead to higher tree incomes because tree products, such as firewood, fodder and fruits were mainly for household consumption, in which case, they did not contribute much to improving household income. In addition, food insecure farmers often sold tree products as a coping strategy to meet their basic needs [14]. In Southern Rwanda, Ngango, Musabanganji [16], found that agroforestry-adopting households had significantly higher FCS than non-adopters. In yet another study in Rwanda, Danso-Abbeam, Baiyegunhi [37] analyzed the determinants of food security in the Northern and Southern provinces using FCS and the Food Insecurity Experience Scale (FIES). The study focused on farming households, but did not analyze any agroforestry-related factor. Apart from Bolarinwa, Ogundari [1] who used a high-frequency panel data set, most of these studies used cross-sectional data and failed to account for the time dimension in analysis. However, Bolarinwa, Ogundari [1] did not analyze any agroforestry-related variables. These studies show that the determinants of food insecurity vary, and the effects of agroforestry are context-specific and depend on how agroforestry is measured. Therefore investigating the factors affecting food security at local levels would provide more practical and nuanced information for decision-making [16, 26].

The main objective of this study is to examine the determinants of severe food insecurity among smallholder farmers using FIES as the measure of food insecurity. A two-period panel dataset drawn from 1,100 households from the Eastern Province of Rwanda is utilized in the study. The study specifically aims to (i) assess changes in food security status over time; (ii) analyze the effects of agroforestry practice on the probability of experiencing severe food insecurity; and (iii) evaluate the role of individual and household demographic, socio-economic and farming characteristics in shaping food insecurity outcomes. By identifying key factors associated with the likelihood of experiencing food insecurity and highlighting how land restoration strategies like agroforestry contribute to it, this study provides insights that may inform future interventions and policy measures to improve

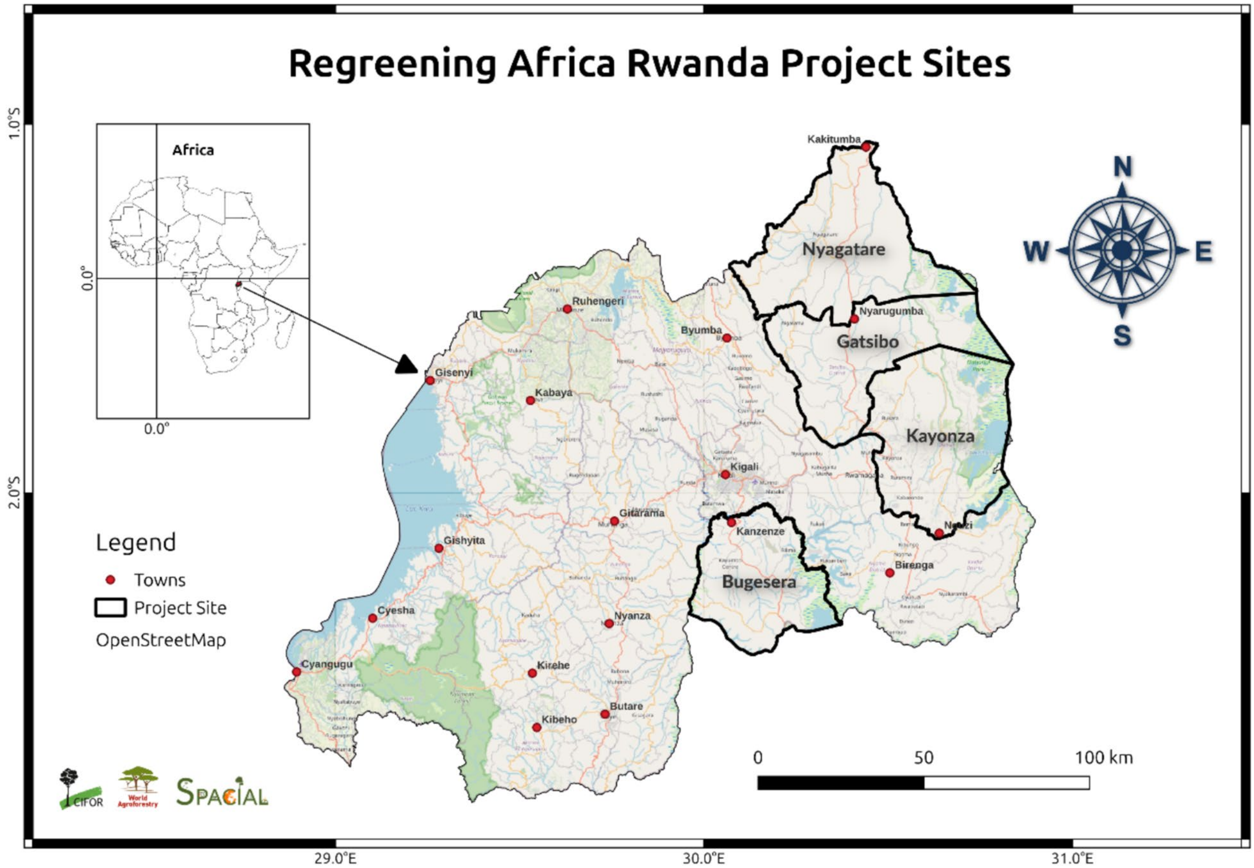

Fig. 1 Map the study sites (Source: World Agroforestry Geo-Science Laboratory (2022))

food security in the study area [9]. Besides, the study provides information on the access and stability of food in the study area and contributes to the growing empirical literature on food insecurity in SSA, using panel data to capture household's dynamic food security status in the study area.

Methods

Description of the study area

Rwanda is a relatively small but densely populated country in Eastern Africa [17]. Due to its geographical location and relief, it receives relatively high rainfall of over 1000 mm/annum [38], which supports most food production. Although Rwanda has made some significant economic gains in the recent past, food insecurity persists [37, 39]. Up to 50% of the population experiences food-related challenges and food insecurity is very acute during the lean months (March to May and September to November) [1, 18, 37].

This study is conducted in four out of seven districts in the Eastern Province of Rwanda, namely Bugesera, Gatsibo, Kayonza and Nyagatare (Fig. 1). The Eastern Province, is dominated by shrubland and wooded savannah and faces high deforestation rates and frequent dry spells which significantly affect food production [39, 40]. About 72% of households in the Eastern Province are smallholder farming households [17]. Since their farm sizes are small, crop production is minimal, forcing them to cultivate throughout the year [10, 14, 41]. Consequently, soil nutrients are depleted and land regeneration does not occur, leading to a repeated cycle of low food production [11, 14]. To improve food production, several initiatives promoting agroforestry and better agricultural practices have been implemented at the national level [14, 35, 42] and specifically in the Eastern Province [43]. These districts were purposively selected because they had been targeted by a land restoration intervention program, Regreening Africa (RA),[1] which was implemented from 2018 to 2023, by World Vision Rwanda in areas that had experienced high levels of land degradation [44].

[1] The program was implemented in Ethiopia, Ghana, Kenya, Mali, Niger, Rwanda, Senegal, and Somalia by five international development organizations including: World Vision International, Catholic Relief Services, CARE International, Oxfam International and SAHEL-Eco. Information on the program can be found on the website: https://regreeningafrica.org/

The main agroforestry interventions were tree planting, tree care and management, and grafting. Prevalent tree species found in smallholders' farms include timber trees like *Eucalyptus spp.*, *Grevillea robusta*, multipurpose trees like *Calliandra calothyrsus*, *Senna spectabilis*, *Markhamia lutea*, and fruit trees such as *Mangifera indica* (mango), *Persea americana* (avocado) and *Cyphomandra betacea* (tree tomato). The program focused on implementing agroforestry practices to restore degraded landscapes, motivated by evidence and existing literature such as [10, 14, 24, 27, 29, 45, 46] that highlight the role of agroforestry as a landscape restoration intervention and its potential to contribute to household income and food security among other ecological and livelihood benefits. One of our study objectives, therefore, is to investigate whether the practice of agroforestry within this context has any measurable effect on food security.

Sampling and data collection

Data for this study were obtained from two surveys conducted by World Agroforestry (ICRAF) in the RA program sites in June 2018 and February 2022. Both surveys were conducted through face-to-face interviews using semi-structured questionnaires. A team of trained enumerators interviewed respondents and entered data into the SurveyCTO© data collection tool on tablets and smartphones. Interviews were mainly done with either heads of households or their spouses. Before data collection, the survey tool was pretested and translated into the local language to ensure clarity and cultural relevance.

The sampling strategy and data collection approach were aligned to ICRAF's impact evaluation strategy for the RA project, ensuring that it was robust and relevant for assessing the program's outcomes [44]. From each district, eight cells[2] were selected randomly. Within each cell, four villages were selected randomly, except for one cell, which had three villages. From the selected villages in each cell, a random sample of 40 households was selected, resulting in an initial sample size of 1280 households. Of these, 1268 households were successfully interviewed in 2018, and 1132 were retraced and interviewed in 2022 [44]. The data collected included household demographic and socio-economic data, membership and participation in social groups, land, livestock and asset ownership, food consumption and food insecurity experience data, farming and agroforestry practices, tree-related information including tree species, tree management and decision-making, tree product use and sale. Households with missing data required for this study were excluded using the listwise deletion approach [47], resulting in a final sample of 1,100 households, evaluated across two survey years.

[2] A cell is an administrative unit comprising several neighboring villages and is the lowest administrative unit where citizens can access basic government services.

Food insecurity indicator

Several indicators have been developed to estimate food insecurity using observed data [48, 49]. In this study, we use the Food Insecurity Experience Scale (FIES), which was developed by the Voices of the Hungry project [50]. FIES is the internationally accepted estimator of the severity of food insecurity experience [49, 51]. FIES is calculated from the standard Food Insecurity Experience Scale Survey Module (FIES-SM) which consists of eight binary response questions aimed at evaluating an individual's access to adequate food [50, 52, 53]. The questions are designed to capture different levels of severity of food insecurity, ranging from worrying about running out of food to going for entire days without eating. The eight questions in the FIES-SM are:

Over the last 12 months,

- Were you worried you would run out of food…?
- Were you unable to eat healthy and nutritious foods…?
- Did you only eat a few kinds of foods…?
- Did you skip a meal…?
- Did you eat less than you thought you should…?
- Did your household run out of food…?
- Were you hungry but did not eat…?
- Did you not eat for a whole day…?

The wording of each question ends with 'because you did not have enough money or resources'. This very specific phrasing emphasizes that the reported behavior or experience is due to a lack of money or other resources, and not voluntary behaviors such as fasting or dieting [52]. Since the recall period is 12 months, FIES also captures the food stability dimension. To define our FIES-related outcome variable, we follow the approach in Tabe-Ojong, Fabinin [6] where we first sum up the FIES raw scores (total scores range from 0 to 8), then generate the outcome variable. This computation is based on the classification of severity of food insecurity experience in Cafiero, Viviani [52]. The outcome used in this study is "food insecurity", which compares households that experienced severe food insecurity (FIES raw scores of 7 or 8) to those that did not (FIES raw scores below 7), capturing the highest level of food insecurity at household level.

Variables used in the study

Food insecurity is influenced by several factors. In this study, we consider various household socio-economic factors, farming practices, and institutional factors, with a particular focus on estimating the effect of agroforestry on household food insecurity. There are different pathways through which agroforestry practice may affect food security. First, agroforestry trees may directly provide food in the form of vegetables, fruits, nuts and seeds [16, 26]. Second, farmers may sell tree products like fruit, timber, fuelwood, herbs, poles and fodder, and use the income to purchase food [10, 16]. Third, through ecosystem services like soil fertility enhancement, agroforestry improves crop production, resulting in better yields [16, 27]. In this study, the effect of agroforestry is estimated using six variables: the number of trees on farms and five dummy variables including: tree establishment in the main cropping field, harvesting tree products from farms and from communal land, selling tree products, and consuming fruit harvested from farm. The expectation is that farmers with more trees on farms, and/or those who harvest tree products for use or sale from their own fields or communal lands would be less likely to experience severe food insecurity compared to those who have less trees or have zero in the binary variables.

Other covariates analyzed are based on theory and previous empirical studies such as [1, 16, 19, 20, 51, 54]. Land size and agricultural practices affect crop production, consequently affecting food insecurity [8, 20, 55]. Households with larger farms were expected to produce more food and be less food insecure [56]. The number of crops grown by the household was also analyzed. Crop diversification allows smallholders to mitigate production and market risks hence we expect an inverse relationship between production and food insecurity [7, 20, 55, 57, 58]. We also estimated the effect of two agricultural practices: the use of chemical fertilizers to improve crop productivity and irrigation to mitigate periods of low rainfall. These two practices were expected to boost crop production, and consequently improve food security [5].

To estimate the effect of access to markets, the distance from the homestead to the nearest [peri]-urban center was also included to capture barriers faced by smallholders in accessing markets to buy food or sell crops [7, 57]. Household membership in community groups was analyzed because these groups allow farmers to participate in collective efforts, share knowledge, for example on good agricultural practices, support each other socially and access resources they can use to improve production [16, 37]. In the absence of income data, we use household assets and household participation in off-farm activities as alternatives. Off-farm activities include casual labor, businesses, and employment, which enable households to earn some income. Household wealth was measured using principal component analysis (PCA)-derived indexes of farm assets, durable household assets and livestock ownership. Following the approach taken by Hughes, Morgan [32], binary asset variables were created for each household and assets negatively correlated with others were excluded based on inter-item correlations. After this tetrachoric correlation matrices were computed for the remaining variables. Principal component factor analysis was then performed on these matrices, and the first principal component used to generate the asset index for each household [32]. Separate indexes were constructed for each category using relevant asset variables. A higher household asset index suggests better economic status and is likely to reduce probability of food insecurity, while farm tools support better crop production [55]. Livestock provides food items such as milk, eggs and meat, but animals can also be sold for income to meet diverse household needs [37]. Food insecurity is also influenced by household demographic and socioeconomic characteristics. We therefore included the age, gender and level of education of the household head and household size in the analysis. A district indicator variable was included to account for district-level factors, and a survey year dummy to capture time effects. A priori expectations of these variables are shown in Appendix 1.

Empirical analysis

The relationship between food insecurity and the explanatory variables may be represented by the following generic model:

$$Y_{it}^{*} = \alpha + \beta_1 X_{it} + u_i + \varepsilon_{it}, \quad (1)$$

where Y_{it}^{*} is a latent variable that determines the outcome, β_1 is a vector of coefficients to be estimated, X_{it} is a vector of independent variables, which includes agroforestry-related variables, u_i are the individual-specific error terms and ε_{it} is the random error term. The outcome variable, Y_i takes the value of 1 if the household experiences severe food insecurity, and $y_{it} = 0$, otherwise, and is represented as:

$$Y_{it} = \begin{cases} 1 if Y_{it}^{*} > 0 \\ 0 otherwise \end{cases}. \quad (2)$$

A random effects (RE) probit model was applied to estimate the relationship between severe food insecurity experience and agroforestry-related factors, household characteristics and farming practices. This model is suitable for panel data with binary dependent variables [59]. It also avoids the incidental parameters problem associated with fixed effects analysis in non-linear models [19, 60, 61]. However, the standard RE probit imposes the restrictive strict exogeneity condition typically associated with RE models, which may be inappropriate due to potential correlation between the error term and explanatory variables. Therefore, following the approach adopted by Ngoma, Mulenga [62] and Tambo, Uzayisenga [19], we employ the correlated random effects (CRE) probit model to relax this assumption and mitigate potential confounding by unobserved heterogeneity. This entails modeling the dependent variable as a function of the means of all time-varying regressors included in X_{it} in Eq. 1 [61, 63]. The time-varying variables include household size, land size, engagement in off-farm activities, household membership to community groups, farm input use and agroforestry-related variables. With this inclusion, Eq. 1 then becomes Eq. 3, where $\bar{X_i}$ is a vector of the means of time-varying variables:

$$Y_{it}^{*} = \alpha + \beta_1 X_{it} + \gamma \bar{X}_i + u_i + \varepsilon_{it}. \quad (3)$$

The probability that a household experienced severe food insecurity is expressed as:

$$Pr(Y_{it} = 1|X_{it}, \bar{X}_i) = \Pr\left(Y_{it}^{*} > 0\right) = \Pr(\alpha + \beta X_{it} + \gamma \bar{X}_i + u_i + \varepsilon_{it} > 0) \quad (4)$$

Assuming ε_{it} is normally distributed, the probability can be rewritten as Eq 5:

$$Pr\left(Y_{it} = 1|X_{it}, \bar{X}_i\right) = \Phi\left(\beta X_{it} + \gamma \bar{X}_i + u_i\right), \quad (5)$$

where ϕ is the cumulative distribution function of the standard normal distribution.

The coefficients estimated by probit models typically represent change in the latent variable, Y_{it}^{*}. Therefore, to provide directly interpretable results, we further estimate marginal effects which are interpreted as the effect of the independent variable on the probability of the dependent variable occurring, that is $Pr\left(Y_{it} = 1|X_{it}, \bar{X}_i\right)$.

Results

Descriptive statistics

Table 1 shows descriptive statistics of the explanatory variables.

The average age of the household head was 47 years, while the average household size was approximately five (4.75). Approximately 22% of households were female-headed. The level of formal education among household heads was relatively low with an average of about four years. Approximately 30% of household heads had no formal education, 60% had primary level education, and 10% had post-primary level education. Most households were subsistence producers, primarily producing crops and rearing some livestock for household consumption, with only 31% of households having sold crops in the previous 12 months. Households generally grew between two and four different crops. Further analysis indicates that only 3% of households had irrigated their farms and almost 30% had used chemical fertilizers on their farms in the previous 12 months (Table 1).

The household asset index comprises livestock, farm tools and equipment, ownership of durable household assets and housing conditions. The asset index ranged from one to six, with an average of 1.71, suggesting modest economic conditions for the households. We analyzed three components of the asset index including livestock, farm assets and durable assets, rather than the overall index in order to understand the contribution of each asset category. The average livestock index was 0.35, indicating a low level of livestock ownership. The average farm asset index (farm equipment and tools) was 0.52, while the household durable assets index had a mean of 1.10 (Table 1). Approximately 38% of households engaged in off-farm activities including businesses, casual and agricultural labor and to a small extent formal employment. Membership in community groups was relatively high, with about 68% of households having members affiliated with such groups. Household access to markets varied depending on the cell in which the household was located with the average distance to the nearest [peri]-urban center being 6.8 km.

Most households practiced agroforestry and had various tree species on their farms, from which they obtained different products. The percentage of households that established more than 10 trees on the main farm was 23%, and 52% of households harvested different tree products. Harvesting of tree products from community land was low, with only 25% of households reporting this. Tree products were mainly harvested for household consumption as only 10% of households sold the products. The provision of food, specifically fruits is important in agroforestry. At least 24% of households harvested fruit from their farms, and 23% of households consumed the fruit harvested from their farms (Table 1). Appendix 2 presents the same descriptive statistics as Table 1 but disaggregated by food insecurity status. There are significant differences between the two categories of households across most of these variables as shown in Appendix 2. However, further empirical analysis should be done to establish statistically significant correlations between these variables and the probability of experiencing severe food insecurity.

Figure 2 shows the distribution of the FIES raw scores by survey year. It reveals a generally high level of food insecurity among households in 2018 and 2022. The median FIES raw score in both 2018 and 2022 was 7, while the average score declined from 6.02 in 2018 to 5.73 in 2022. This indicates that food insecurity was slightly less severe in 2022 compared to 2018. Only about 7% and 11% of households in 2018 and 2022, respectively, had a raw score of 0, meaning they did not experience any level of food insecurity. Table 2 shows the levels of

Table 1 Descriptive statistics

Variable description	Mean	Std. Dev	Confidence intervals
Outcome variable			
Household experienced food insecurity, 1 = yes	62%		[59%–64%]
Continuous variables			
Age of the household head	46.69	14.38	[46.1–47.3]
Household size	4.75	1.82	[4.69–4.84]
Overall asset index	1.71	1.07	[1.67–1.76]
- Livestock index	0.35	0.45	[0.33–0.37]
- Farm assets index	0.52	0.48	[0.50–0.54]
- Durable assets index	1.10	0.76	[1.07–1.14]
Household's land size in hectares	0.36	0.45	[0.34–0.37]
Number of crops grown in previous 12 months	3.18	2.00	[3.09–3.26]
Number of trees on farm	28.62	36.82	[27.1–30.2]
Distance to the administrative office	1.86	1.72	[1.79–1.94]
Distance to the nearest [peri]-urban center in kilometers	6.80	5.19	[6.62–7.05]
Categorical variables	Percentages		
Gender of the household head (1 = female)	22%		[20%–23%]
Level of education of the household head			
- None	30%		[28%–32%]
- Primary level	60%		[58%–62%]
- Secondary level	7%		[6%–8%]
- Tertiary level	3%		[2.6%–4%]
Membership to groups, 1 = yes	68%		[66%–70%]
Engagement in off-farm activities, 1 = yes	38%		[36%–40%]
Household practiced irrigation, 1 = yes	3%		[2.5%–4%]
Household applied chemical fertilizers, 1 = yes	30%		[28%–32%]
Household sold crops produced in previous 12 months, 1 = yes	31%		[29%–33%]
Household established > 10 trees in main crop field, 1 = yes	23%		[21%–24%]
Household harvested any tree product from their farms, 1 = yes	52%		[49%–54%]
Household sold tree products, 1 = yes	10%		[9%–11%]
Household obtained tree products from community land, 1 = yes	25%		[23%–27%]
Household consumed fruit harvested from own farm, 1 = yes	23%		[22%–25%]
Number of observations	N = 2,200		

food insecurity among households in 2018, 2022 and in both survey years.

The households are divided into four levels: food secure (FIES = 0), mild food insecure (FIES = 1—3), moderate food insecure (FIES = 4—6) and severe food insecure (FIES = 7—8). It is evident from Table 2 that the level of food insecurity among sampled households was very high. At baseline, approximately 63% of households were severely food insecure, 18% were moderately food insecure, 12% were mildly food insecure and 7% did not experience any food insecurity. The percentage of households in the mild and moderate food insecure categories remained unchanged in both 2018 and 2022. However, the percentage of households that did not experience any form of food insecurity increased from 7% in 2018 to 10% in 2022, while the percentage of severely food insecure households declined from 63 to 60%. This indicates that there were slight improvements in household food security status in general.

Figure 3 shows the percentage of households that provided affirmative responses to each of the FIES-SM questions, reflecting specific food insecurity experiences including concerns about food availability, inability to access sufficient food quantity and impact on dietary quality. Figure 3 has a slightly negative gradient with the percentages depicting the prevalence of food insecurity experiences. From the figure, there are significant concerns about food availability among households. More households affirmed the questions reflecting concerns about food availability and quality, including worrying

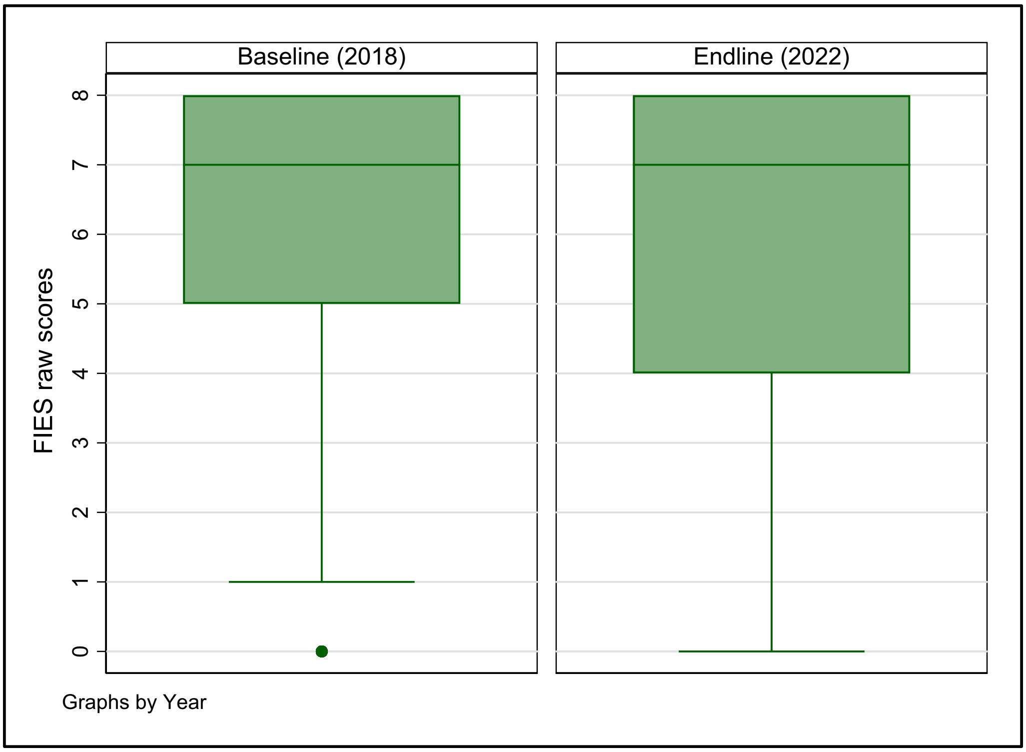

Fig. 2 Distribution of FIES raw scores by survey year

Table 2 Distribution of households across food insecurity levels

Level	Baseline (2018) (%)	Endline (2022) (%)	Average (%)
Food secure	7	10	9
Mild food insecure	12	12	12
Moderate food insecure	18	18	18
Severe food insecure	63	60	62

about lacking food or not eating what they would prefer or eating a limited range of food. Household food insecurity also manifested in extreme coping strategies like running out of food, skipping meals or not eating for a whole day. However, the less households adopted extreme strategies like going an entire day without food.

Empirical results

Before analysis, we assessed multicollinearity in the explanatory variables using variance inflation factors (VIF) and found a mean VIF of 2.55 (Appendix 3), indicating that multicollinearity was not a problem. Table 3 shows the marginal effects of the regression analyses. Column 2 shows the results of the standard RE probit model and Column 3 are the results from the CRE probit model. Column 3 reveals that only a few factors significantly affected food insecurity in the study area. This suggests that food security is influenced by a broader range of factors, some of which were not captured in the study. From the results, the number of foods cultivated, households engaging in sale of crops, household size, distance to the administrative office and the time dummy significantly correlated with severe food insecurity. An extra person in the household correlated with a 2% increase in the probability of severe food insecurity, highlighting the strain that larger household sizes can place on available resources including food. The role of household assets was also analyzed. A unit increase in the durable assets index was associated with a 21% decrease in the probability of severe food insecurity.

In this study, crop diversity was measured as the number of different crops produced by the household in the previous season. Table 3 shows that producing one more crop correlated with a 1.3% reduction in the probability of severe food insecurity. Households that sold crops in the previous year had an 8% reduction in the probability of severe food insecurity.

The proximity of households to the local administrative offices is also a significant factor. Households living closer to the cell administrative offices were more likely to experience severe food insecurity than those living further

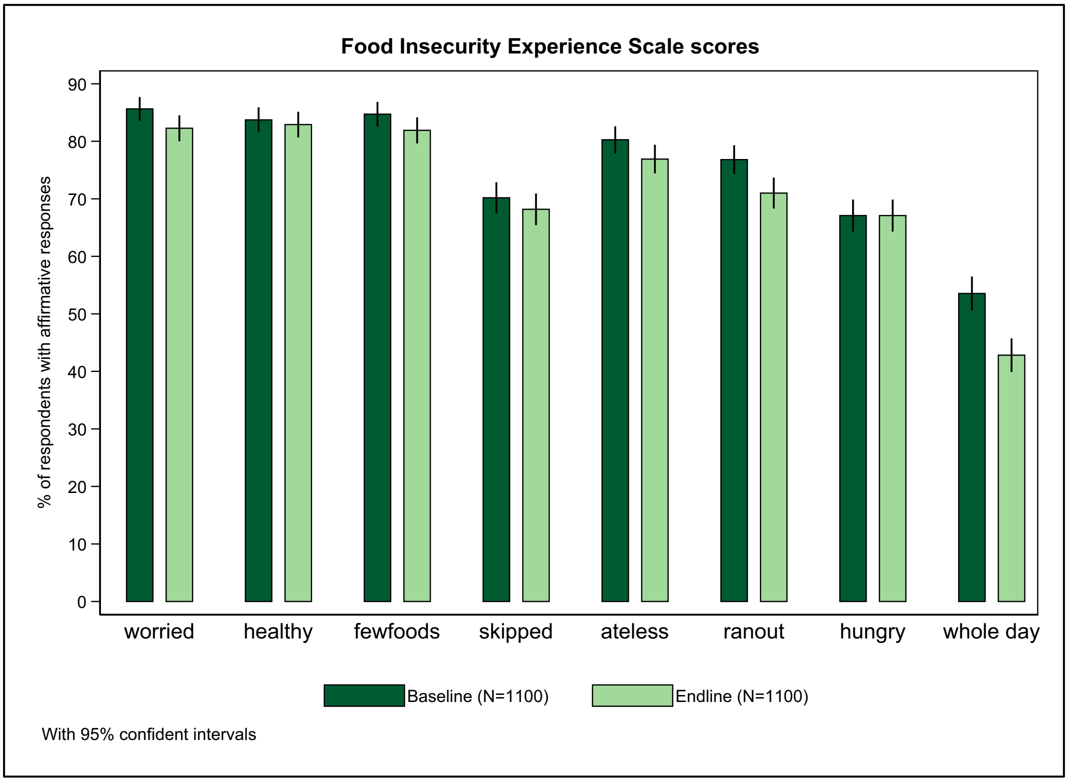

Fig. 3 Households affirmative responses to FIES-RM questions by survey year

away. There were also some significant differences in the results due to household location. Households in Gatsibo district had an 8% reduction in probability of severe food insecurity while households in Kayonza district had a 12% increase in probability of severe food insecurity relative to households in Bugesera district. The time effects were also statistically significant, suggesting that the likelihood of severe food insecurity in 2022 was significantly lower than it was in 2018, by 11%. Additionally, this study also estimated the effect of six agroforestry-related factors. None of these factors were significantly correlated with severe food insecurity. The lack of statistical significance implies that the impact of the agroforestry-related variables might not have been substantial enough to reduce food insecurity within the study's duration.

Discussion

Factors affecting food insecurity

Food insecurity can be linked to several factors including household demographic and socio-economic factors, farming practices, environmental conditions and institutional factors. This study revealed that household size significantly affected food insecurity. Larger households were associated with an increased probability of severe food insecurity. Past studies including [16, 56, 64], have consistently demonstrated that larger households are more likely to experience food insecurity. Given the high demand for food in such households, food insecurity can occur if the factors of production at household level remain the same. Therefore, larger households should prioritize maximizing food production from their farms in the short-term [16].

Our findings also show that the household durable asset index had the largest effect size on reducing the probability of severe food insecurity emphasizing the role of household economic status in food security. Households with more durable assets may be better financially endowed enabling them to afford food more easily. Household assets serve as a buffer against economic instability, allowing wealthier households to better withstand shocks and maintain food production even in adverse conditions. Despite the correlation between durable assets and food insecurity, it is important to note that some assets may not be easily liquidated to buy food, therefore we recommend use of other measures of household's economic status like income in future studies, to give a better picture of the effect of household income levels on food insecurity experience. Besides, the effect of wealth measured through assets on food security was sometimes unclear

Table 3 Factors associated with the probability of experiencing severe food insecurity (marginal effects)

	Standard RE probit	CRE probit
Agroforestry-related variables		
Number of trees on farm	−0.0001 (0.0003)	−0.0001 (0.0004)
Household consumed fruit from farm, 1 = yes	0.013 (0.028)	0.015 (0.038)
Household established > 10 trees in main field, 1 = yes	−0.017 (0.025)	−0.053 (0.035)
Household harvested any tree product from farm, 1 = yes	0.030 (0.025)	0.054 (0.033)
Household sold tree products, 1 = yes	0.023 (0.034)	0.053 (0.047)
Households harvested a tree product from community land, 1 = yes	−0.019 (0.027)	−0.013 (0.036)
Other variables and controls		
Gender of household head, 1 = female	0.020 (0.025)	0.018 (0.024)
Level of education of the household head—none		
Primary level education	−0.004 (0.022)	0.002 (0.022)
Secondary level education	0.007 (0.042)	0.017 (0.041)
Tertiary level education	−0.023 (0.067)	−0.024 (0.067)
Age of the household head	−0.0004 (0.001)	0.000 (0.001)
Household engaged in off-farm activities, 1 = yes	0.058*** (0.020)	0.007 (0.029)
Household membership to groups, 1 = yes	−0.057*** (0.020)	−0.028 (0.031)
Household size	0.019*** (0.005)	0.021*** (0.005)
Livestock index	−0.07*** (0.022)	−0.04 (0.035)
Farm asset index	−0.024 (0.025)	−0.015 (0.034)
Durable assets index	−0.22*** (0.015)	−0.207*** (0.016)
Household practiced irrigation, 1 = yes	0.033 (0.050)	0.059 (0.072)
Household applied fertilizers, 1 = yes	−0.044** (0.021)	−0.005 (0.032)
Land size in hectares	−0.043* (0.023)	−0.006 (0.031)
Number of crops grown in previous year	−0.013** (0.005)	−0.013** (0.007)
Household sold crops in previous year, 1 = yes	−0.084*** (0.02)	−0.081*** (0.02)
Distance to the administrative office in kilometers	−0.023*** (0.006)	−0.023*** (0.006)
Distance to nearest [peri]-urban center in kilometers	−0.001 (0.002)	−0.001 (0.002)
Time effects included (0 = 2018, 1 = 2022)	−0.085*** (0.023)	−0.094*** (0.027)
District dummies included	Yes	Yes
Mean of time-varying variables included	No	Yes
Rho	0.10	0.11
Number of observations	2200	2200

Standard errors in parentheses; * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

[21]. However, other household assets including livestock and farm tools and equipment, were not statistically significant.

With regard to farming practices, the findings show that cultivating a variety of crops reduces the likelihood of severe food insecurity. This finding aligns with other studies from sub-Saharan Africa that demonstrate the benefits of crop diversification. Previous studies, for example Morrissey, Reynolds [7] found that in Uganda, crop diversification was strongly correlated with fewer food inadequate months and higher household dietary diversity, while Mango, Makate [58] and Mango, Zamasiya [56] found that crop diversification resulted in better food consumption scores (FCS) and lower household food insecurity access scores in Malawi and Zimbabwe, respectively. Habtemariam, Gornott [57] made the same conclusion from a study in Tanzania, but measured food security in terms of dietary diversity. Ng'endo, Bhagwat [21], however, found no link between crop diversity and food security in western Kenya. Diversifying crop production enables smallholders to better manage production and market risks and allows them to stagger their production which ensures a more consistent supply of food throughout the year [20, 58]. The production of different crops enhances the diversity of diets among households, an important dimension of food security. It is therefore a strategy that could be employed to reduce severe food insecurity in the study area.

Engaging in local markets enables households to earn an income and encourages better agricultural practices and investment in crop production. Earnings may facilitate purchase of food items not produced on farm, and can reduce food insecurity [21]. The sale of crops is beneficial if it arises from surplus production. However, some studies, reported that households in SSA sometimes sell crops after harvest even without being self-sufficient themselves [9, 11]. This strategy is employed to meet immediate cash needs or to prevent post-harvest losses of perishable produce, despite the risk of future food insecurity. This can expose households to severe food insecurity in future periods. A finding by Ngango, Musabanganji [16] showed that the FCS reduced with increased quantity of agricultural produce sold in the market, highlighting the food insecurity risks smallholder households face in selling agricultural produce after harvest. Further investigation is needed to determine whether households sold their crops and later repurchased the same crops they had sold.

Besides household factors and farming practices, institutional factors are also important. The proximity of households to cell administrative offices affected the probability of severe food insecurity. Our results suggest households further away from administrative offices may experience a lower probability of severe food insecurity. This may be due to a higher level of self-sufficiency and less reliance on government support programs. However, further analysis is required to disentangle other systemic issues that might be associated with proximity to administrative offices, and which may affect food insecurity in the population such as resources for better production. In most areas in the study area, market areas are integrated with administrative offices, and this can increase reliance on cash crops or purchased food. Households located further away from administrative offices and markets may avoid price shocks or income instability that are associated with cash-based economies, by producing more crops leading them to be less susceptible to severe food insecurity.

Methodologically, our findings demonstrate that some of the factors that significantly affect food insecurity in the standard RE probit model are not significant in the CRE probit model. In the former model, the significant covariates may include error terms of unobserved factors thus inflating the significance levels if they were correlated. Once unobserved heterogeneity is controlled for by the CRE probit model, the significant relationships previously observed do not hold, suggesting that the earlier significance may have been due to confounding factors or omitted variable bias. The variables that are statistically significant in both models show only marginal differences in the coefficients, meaning that the effect of these variables was relatively consistent across the two models.

The role of agroforestry in reducing food insecurity

Agroforestry is generally associated with a range of ecological and socio-economic benefits, but the relationship between agroforestry and food insecurity is complex [26]. Our findings show that agroforestry-related factors did not significantly affect the probability of severe food insecurity. This does not suggest that agroforestry does not affect food security generally but implies that the effects of the variables measured did not reflect significant changes due to the short project implementation timeframe. As such, planted trees may not have been mature enough to yield the expected improvements in food security. Since Rwanda is generally characterized by high food insecurity [4], it is likely that the observed slight improvements in food security between 2018 and 2022 are due to external factors. Such factors may include seasonal variations, other ongoing development programs, or short-term coping mechanisms adopted by households. The statistically significant time effects also corroborate the descriptive findings which show slightly lower food insecurity levels in 2022. This suggests that there could also have been higher-level factors that generally affected the study area as a whole and may have led to the slightly less food insecurity experienced by households in 2022.

The lack of statistical significance of agroforestry-related variables may also be explained by other factors such as low levels of adoption and adopting unsuitable tree species. In regions with very small land sizes, agroforestry practices, including tree planting, can be challenging. This is because the limited land may not be sufficient to accommodate both crops and trees effectively [11, 24, 55], leading to low adoption levels. Farmers in such areas prioritize immediate crop production over long-term agroforestry investments, reducing the potential of agroforestry to contribute to food security. Immediate economic pressures may also compel people to focus on short-term yields rather than long-term sustainability [55]. It may be necessary to tailor agroforestry systems to small-size plots in order to optimize land use.

Integrating unsuitable tree species may also fail to have the desired effect on food security [55]. Such species may not improve soil productivity, directly provide food or supply saleable tree products. In this study, the most prevalent tree species in farms were exotic trees, such as *Eucalyptus spp*., which may not directly reduce food insecurity in the short term. The fruit trees planted during the study period, such *Mangifera indica* (mango), *Persea americana* (avocado) and *Cyphomandra betacea* (tree tomato), may not have started fruiting by the time the surveys were done, hence may not have had a significant effect on severe food insecurity. So, while agroforestry holds significant long-term potential for improving food security, realizing these benefits requires targeted policy support and the promotion of context and ecologically appropriate species. Policy makers could prioritize continued integration of the fruit trees listed above including mango, avocado, and tree tomato; timber species from which farmers can earn incomes (such as *Grevillea robusta*), and multipurpose leguminous trees which enhance soil fertility (such as *Gliricidia sepium* and *Calliandra calothyrsus*) within smallholder systems, as these have demonstrated both economic and ecological benefits in similar contexts [65]. It is also important to conduct farmer training to promote uptake of different tree species. Tree-planting could also be incentivized by increasing access to planting materials. The effectiveness of agroforestry systems can also be undermined by environmental challenges. While agroforestry seeks to build resilience to challenges such as drought, soil degradation and climate change, benefits may not be realized in the short term if these conditions are too harsh or unpredictable, causing the expected advantages of integrating trees into farming systems not to materialize as expected.

Conclusion

This study sought to investigate factors affecting food insecurity among smallholder farmers in Eastern Rwanda. The results highlighted the fact that food insecurity was high in the study area and warrants attention. The empirical findings indicated that farming practices like the number of crops produced, and household socioeconomic characteristics like household size and durable assets played a more significant role in food insecurity than agroforestry-related factors in the short-term. The time taken for agroforestry systems to mature and have the desired impact on food security outcomes was identified as an important factor to be considered in light of the prevailing food insecurity situation, particularly in rural areas of the country such as the Eastern Province. Agroforestry interventions can therefore be adopted as a long-term food security improvement measure.

These findings provide a basis for making various policy suggestions. It is recommended that interventions that can address the immediate high level of food insecurity in the study area be identified and supported. It might be better to promote measures that increase the socio-economic status of households to enable them to access food more easily or increase the capacity of farmers to produce more from their farms in the short term. While market-oriented production should be encouraged, improving storage facilities and practices could help households manage their food resources better. For mid- to long-term agroforestry interventions, farmers must be encouraged to adopt the right tree species and follow best practices to integrate them in crop lands. The impact of agroforestry can better be evaluated after maturation of planted trees.

For future studies, data such as crop productivity and income would be necessary to improve such analyses. We found, for example, that households that marketed crops had a significant effect on food insecurity, but this was only based on a binary variable. To understand the extent of such contribution, data on how much income are obtained from sale of crops vis-a-vis other sources of household income, including tree income would be required. Furthermore, we recommend that future research employ experimental methods to better understand causal pathways and the long-term effects of specific species and tree management practices.

Appendix 1

See Table 4

Table 4 A priori expectations of regression covariates

Description	Type of variable	Expected effect on food security
Number of trees on farm	Continuous	+
Trees established in the main cropping field	Dummy	+
Households harvested tree products from their farms	Dummy	+
Households harvested tree products from communal land	Dummy	+
Households sold tree products within the year	Dummy	+
Households consumed fruit harvested from farms	Dummy	+
Land size	Continuous	+
Number of crops grown	Continuous	+
Use of chemical fertilizer	Dummy	+
Practice of irrigation	Dummy	+
Distance from homestead to nearest market	Continuous	±
Membership of household members to groups	Dummy	±
Farm asset index	Continuous	+
Durable assets index	Continuous	+
Livestock index	Continuous	+
Gender of household head	Dummy	±
Age of household head	Continuous	±
Level of education of household head	Categorical	+
Household size	Continuous	±
District fixed effects	Used to control district level effects	
Time fixed effects	Used to control macro-level issues affecting the entire sample	

Appendix 2

See Table 5

T-test used for continuous variables and *prtest* two-sample for proportions used to check differences between percentages of binary variables. Standard errors in parentheses. $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

Table 5 Descriptive statistics by food security status

Variable description	Food insecure (1)	Not food insecure (0)	Difference (0–1)
Continuous variables			
Age of the household head	46.60	46.84	0.24 (0.63)
Household size	4.67	4.91	0.24*** (0.80)
Overall asset index	1.33	2.33	1.00*** (0.04)
- Livestock index	0.26	0.49	0.22*** (0.02)
- Farm assets index	0.41	0.70	0.29*** (0.02)
- Durable assets index	0.85	1.51	0.66*** (0.03)
Household's land size in hectares	0.29	0.46	0.18*** (0.02)
Number of crops grown in previous 12 months	2.97	3.51	0.54*** (0.09)
Number of trees on farm	24.98	34.43	9.45*** (1.60)
Distance to the administrative office	1.85	1.89	0.04 (0.08)
Distance to the nearest [peri]-urban center in kilometers	6.80	6.89	0.10 (0.23)
Categorical variables	Proportions	Proportions	
Gender of the household head (1 = female)	0.25	0.17	−0.08*** (0.021)
Level of education of the household head			
- None	0.33	0.24	−0.10*** (0.019)
- Primary level	0.59	0.62	0.03 (0.021)
- Secondary level	0.05	0.09	0.04*** (0.011)
- Tertiary level	0.02	0.05	0.03*** (0.009)
Membership to groups, 1 = yes	0.63	0.77	0.14*** (0.021)
Engagement in off-farm activities, 1 = yes	0.42	0.31	−0.11*** (0.020)
Household practiced irrigation, 1 = yes	0.025	0.042	0.02** (0.008)
Household applied chemical fertilizers, 1 = yes	0.23	0.41	0.19*** (0.020)
Household sold crops produced in previous 12 months, 1 = yes	0.22	0.45	0.22*** (0.020)
Household established > 10 trees in main crop field, 1 = yes	0.20	0.27	0.07*** (0.019)
Household harvested any tree product from their farms, 1 = yes	0.48	0.57	0.09*** (0.022)
Household sold tree products, 1 = yes	0.08	0.14	0.05*** (0.014)
Household obtained tree products from community land, 1 = yes	0.22	0.30	0.09*** (0.019)
Household consumed fruit harvested from own farm, 1 = yes	0.22	0.26	0.05** (0.019)

Appendix 3

See Table 6

Table 6 Variance inflation factors table

Variable description	VIF	1/VIF
Gender of household head	1.27	0.78
i. Level of education of the household head		
Primary level	1.5	0.67
Secondary level	1.3	0.77
Tertiary level	1.21	0.83
Age of household head	1.49	0.67
Household engaged in off-farm activities	2.46	0.41
Household belongs to community level groups	2.63	0.38
Household size	1.2	0.84
Livestock index	3.49	0.29
Farm asset index	3.5	0.29
Durable assets index	1.86	0.54
Household practiced irrigation	2.21	0.45
Household applied chemical fertilizer	2.82	0.36
Land size	3.04	0.33
Number of crops grown in previous year	2.75	0.36
Household sold crops in previous year	1.22	0.82
Number of trees on household farm	3.45	0.29
Household consumed fruit harvested from farm	3.47	0.29
Household established more than 10 new trees on main crop field	2.99	0.33
Household harvested at least one tree product from farm	3.62	0.28
Household sold at least one tree product harvested from farm	2.49	0.40
Household harvested at least two tree products from communal land	3.47	0.29
Distance to administrative office	1.36	0.74
Distance to nearest urban/peri-urban center	1.17	0.85
Time dummy	2.51	0.40
i. District		
Gatsibo district	1.69	0.59
Kayonza district	1.82	0.55
Nyagatare district	1.71	0.58
Mean land size	3.32	0.30
Mean off-farm participation	2.53	0.39
Mean group membership	2.64	0.38
Mean number of crops grown	2.7	0.37
Mean livestock index	3.93	0.25
Mean farm asset index	3.92	0.26
Mean number of trees on farm	3.73	0.27
Mean—household established > 10 trees on main crop field	2.87	0.35
Mean—household harvested at least one tree product from farm	3.6	0.28
Mean—household sold at least one tree product harvested from farm	2.67	0.38
Mean—household harvested at least two tree products from communal land	3.56	0.28
Mean—household practiced irrigation	2.23	0.45
Mean—household applied chemical fertilizer	2.81	0.36
Mean—household consumed fruit harvested from farm	3.27	0.31
Mean VIF	2.55	

Appendix 4

See Table 7

Standard errors in parentheses; p-values in square brackets; * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 7 Factors associated with the probability of experiencing severe food insecurity (marginal effects)

	Standard RE probit	CRE probit
Agroforestry-related variables		
Number of trees on farm	−0.0001 (0.0003) [0.896]	−0.0001 (0.0004) [0.951]
Household consumed fruit from farm, 1 = yes	0.013 (0.028) [0.659]	0.015 (0.038) [0.702]
Household established > 10 trees in main field, 1 = yes	−0.017 (0.025) [0.487]	−0.053 (0.035) [0.135]
Household harvested any tree product from farm, 1 = yes	0.033 (0.024) [0.174]	0.054 (0.033) [0.105]
Household sold tree products, 1 = yes	0.023 (0.034) [0.488]	0.053 (0.044) [0.235]
Households harvested a tree product from community land, 1 = yes	−0.019 (0.027) [0.558]	−0.013 (0.036) [0.726]
Other variables and controls		
Gender of household head, 1 = female	0.020 (0.025) [0.415]	0.018 (0.024) [0.460]
Level of education of the household head—none		
Primary level education	−0.004 (0.022) [0.867]	0.002 (0.022) [0.927]
Secondary level education	0.007 (0.042) [0.869]	0.017 (0.041) [0.682]
Tertiary level education	−0.023 (0.067) [0.727]	−0.024 (0.067) [0.724]
Age of the household head	−0.0004 (0.001) [0.642]	0.000 (0.001) [0.966]
Household engaged in off-farm activities, 1 = yes	0.058*** (0.020) [0.004]	0.007 (0.029) [0.802]
Household membership to groups, 1 = yes	−0.057*** (0.020) [0.007]	−0.028 (0.031) [0.357]
Household size	0.019*** (0.005) [0.000]	0.021*** (0.005) [0.000]
Livestock index	−0.07*** (0.022) [0.001]	−0.04 (0.035) [0.201]
Farm asset index	−0.024 (0.025) [0.369]	−0.015 (0.034) [0.652]
Durable assets index	−0.22*** (0.015) [0.000]	−0.207*** (0.016) [0.000]
Household practiced irrigation, 1 = yes	0.033 (0.050) [0.487]	0.059 (0.072) [0.412]
Household applied fertilizers, 1 = yes	−0.044** (0.021) [0.040]	−0.005 (0.032) [0.873]
Land size in hectares	−0.043* (0.023) [0.064]	−0.006 (0.031) [0.836]
Number of crops grown in previous year	−0.013** (0.005) [0.010]	−0.013** (0.007) [0.047]
Household sold crops in previous year, 1 = yes	−0.084*** (0.02) [0.000]	−0.081*** (0.02) [0.000]
Distance to the administrative office in kilometers	−0.023*** (0.006) [0.000]	−0.023*** (0.006) [0.000]
Distance to nearest [peri]-urban center in kilometers	−0.001 (0.002) [0.505]	−0.001 (0.002) [0.579]
Time effects included (0 = 2018, 1 = 2022)	−0.085*** (0.023) [0.000]	−0.094*** (0.027) [0.000]
District dummies included	Yes	Yes
Mean of time-varying variables included	No	Yes
Rho	0.10	0.11
Number of observations	2200	2200

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Author contributions
HK: conceptualization, methodology, data analysis and interpretation and writing the manuscript; STK: conceptualization, supervision, writing the manuscript; DJ: conceptualization, supervision, writing the manuscript; WF: methodology and writing the manuscript. All authors read and approved the final manuscript.

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Data availability
Data are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate
This study was approved by the Ethics Committee at the Faculty of Natural and Agricultural Sciences, University of Pretoria, South Africa (NAS298/2021).

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

Author details
[1]Department of Agricultural Economics, Extension and Rural Development, University of Pretoria, Hatfield, Pretoria, South Africa. [2]Impact Assessment and Acceleration Unit, World Agroforestry (ICRAF), CIFOR-ICRAF, Gigiri, Nairobi, Kenya. [3]CIRAD, UMR G-EAU, Hatfield, Pretoria 0028, South Africa. [4]G-EAU, Univ Montpellier, AgroParisTech, BRGM, CIRAD, INRAE, Institut Agro, IRD, Montpellier, France.

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References

1. Bolarinwa OD, Ogundari K, Aromolaran AB. Intertemporal evaluation of household food security and its determinants: evidence from Rwanda. Food Secu. 2020;12:179–89.
2. Magrini E, Vigani M. Technology adoption and the multiple dimensions of food security: the case of maize in Tanzania. Food secur. 2016;8:707–26.
3. Pinstrup-Andersen P. Food security: definition and measurement. Food Secur. 2009;1:5–7.
4. FAO, IFAD, UNICEF, WFP, WHO. The state of food security and nutrition in the world 2024 - Financing to end hunger, food insecurity and malnutrition in all its forms. Rome; 2024.
5. Awazi NP, Tchamba N. Enhancing agricultural sustainability and productivity under changing climate conditions through improved agroforestry practices in smallholder farming systems in sub-Saharan Africa. Afr J Agric Res. 2019;14(7):379–88.
6. Tabe-Ojong MPJ, Fabinin AN, Minkoua Nzié JR, Molua EL, Fonkeng EE. Organic soil amendments and food security: evidence from Cameroon. Land Degrad Dev. 2023;34(4):1159–70.
7. Morrissey K, Reynolds T, Tobin D, Isbell C. Market engagement, crop diversity, dietary diversity, and food security: evidence from small-scale agricultural households in Uganda. Food Secur. 2024;16(1):133–47.
8. Giller KE, Delaune T, Silva JV, van Wijk M, Hammond J, Descheemaeker K, et al. Small farms and development in sub-Saharan Africa: farming for food, for income or for lack of better options? Food Secur. 2021;13(6):1431–54.
9. Frelat R, Lopez-Ridaura S, Giller KE, Herrero M, Douxchamps S, Djurfeldt AA, et al. Drivers of household food availability in sub-Saharan Africa based on big data from small farms. Proc Natl Acad Sci. 2016;113(2):458–63.
10. Ding H, Yu T, Levin D, Warburton J, Reytar K, Fang R, et al. Tackling the challenges of assessing socioeconomic impacts of farmland restoration: the case of Malawi. Ecol Ind. 2023;148: 110068.
11. Giller KE. The food security conundrum of sub-Saharan Africa. Glob Food Sec. 2020;26: 100431.
12. Barbier EB, Hochard JP. Land degradation and poverty. Nat Sustain. 2018;1(11):623–31.
13. Luis A, Bravo-Ureta BE. Natural resource management and household well-being: the case of POSAF-II in Nicaragua. World Dev. 2017;99:42–59.
14. Ndoli A, Mukuralinda A, Schut AG, Iiyama M, Ndayambaje JD, Mowo JG, et al. On-farm trees are a safety net for the poorest households rather than a major contributor to food security in Rwanda. Food Secur. 2021;13:685–99.
15. Trudell JP, Burnet ML, Ziegler BR, Luginaah I. The impact of food insecurity on mental health in Africa: a systematic review. Soc Sci Med. 2021;278: 113953.
16. Ngango J, Musabanganji E, Maniriho A, Nkikabahizi F, Mukamuhire A, Ng'ombe JN. Does agroforestry contribute to household food security? A micro-perspective from southern Rwanda. Forest Policy Econ. 2024;165: 103252.
17. NISR. Fifth Rwanda Population and Housing Census, 2022. Main Indicators Report. Kigali, Rwanda: National Institute of Statistics of Rwanda; 2023.
18. Nsabimana A, Bali Swain R, Surry Y, Ngabitsinze JC. Income and food Engel curves in Rwanda: a household microdata analysis. Agric Food Econ. 2020;8:1–20.
19. Tambo JA, Uzayisenga B, Mugambi I, Bundi M. Do plant clinics improve household food security? Evidence from Rwanda. J Agric Econ. 2021;72(1):97–116.
20. MacLaren C, Aliyu KT, Waswa W, Storkey J, Claessens L, Vanlauwe B, et al. Can the right composition and diversity of farmed species improve food security among smallholder farmers? Front Sustain Food Syst. 2022;6: 744700.
21. Ngendo M, Bhagwat S, Keding GB. Influence of seasonal on-farm diversity on dietary diversity: a case study of smallholder farming households in Western Kenya. Ecol Food Nutr. 2016;55(5):403–27.
22. Gupta SR, Dagar JC, Teketay D. Agroforestry for rehabilitation of degraded landscapes: achieving livelihood and environmental security. Agrofor Degrad Landscapes. 2020;1:23–68.
23. Cyamweshi R, Kuyah S, Mukuralinda A, Ngango J, Mbaraka S, Manirere J, et al. Farming with trees for soil fertility, moisture retention and crop productivity improvement: perceptions from farmers in Rwanda. Small-Scale For. 2023;22:1–19.
24. Mwase W, Sefasi A, Njoloma J, Nyoka BI, Manduwa D, Nyaika J. Factors affecting adoption of agroforestry and evergreen agriculture in Southern Africa. Environ Nat Resour Res. 2015;5(2):148.
25. Dollinger J, Jose S. Agroforestry for soil health. Agrofor Syst. 2018;92:213–9.
26. Duffy C, Toth GG, Hagan RP, McKeown PC, Rahman SA, Widyaningsih Y, et al. Agroforestry contributions to smallholder farmer food security in Indonesia. Agrofor Syst. 2021;95(6):1109–24.
27. Coulibaly JY, Chiputwa B, Nakelse T, Kundhlande G. Adoption of agroforestry and the impact on household food security among farmers in Malawi. Agric Syst. 2017;155:52–69.
28. De Giusti G, Kristjanson P, Rufino MC. Agroforestry as a climate change mitigation practice in smallholder farming: evidence from Kenya. Clim Change. 2019;153(3):379–94.
29. Mukhlis I, Rizaludin MS, Hidayah I. Understanding socio-economic and environmental impacts of agroforestry on rural communities. Forests. 2022;13(4):556.
30. Miller DC, Muñoz-Mora JC, Rasmussen LV, Zezza A. Do trees on farms improve household well-being? Evidence from national panel data in Uganda. Front For Global Change. 2020;3:101.
31. Castle SE, Miller DC, Ordonez PJ, Baylis K, Hughes K. The impacts of agroforestry interventions on agricultural productivity, ecosystem

services, and human well-being in low-and middle-income countries: a systematic review. Campbell Syst Rev. 2021;17(2):1–52.
32. Hughes K, Morgan S, Baylis K, Oduol J, Smith-Dumont E, Vågen T-G, et al. Assessing the downstream socioeconomic impacts of agroforestry in Kenya. World Dev. 2020;128: 104835.
33. Miller DC, Ordoñez PJ, Brown SE, Forrest S, Nava NJ, Hughes K, et al. The impacts of agroforestry on agricultural productivity, ecosystem services, and human well-being in low-and middle-income countries: an evidence and gap map. Campbell Syst Rev. 2020;16(1):1066.
34. Malan M, Berkhout E, Duchoslav J, Voors M, Van Der Esch S. Socioeconomic impacts of land restoration in agriculture: a systematic review. Q Open. 2024;4(2):1–17.
35. Verdone M, Seidl A. How do the risk preferences of smallholder farmers affect the attractiveness of restoration activities? Evidence from forest and agricultural land in Rwanda. J Dev Agric Econ. 2016;8(9):200–14.
36. Singh P, Choudhary BB, Dwivedi R, Arunachalam A, Kumar S, Dev I. Agroforestry improves food security and reduces income variability in semi-arid tropics of central India. Agrofor Syst. 2023;97(4):509–18.
37. Danso-Abbeam G, Baiyegunhi LJ, Laing MD, Shimelis H. Understanding the determinants of food security among rural farming households in Rwanda. Ecol Food Nutr. 2022;61(1):1–19.
38. Jonah K, Wen W, Shahid S, Ali MA, Bilal M, Habtemicheal BA, et al. Spatiotemporal variability of rainfall trends and influencing factors in Rwanda. J Atmos Solar Terr Phys. 2021;219: 105631.
39. NISR. Rwanda: Comprehensive Food Security and Vulnerability Analysis. Kigali, Rwanda: National Institute of Statistics of Rwanda; 2021.
40. MinEnv. Rwanda Forest Cover Mapping. Kigali: Ministry of Environment; 2019.
41. Singirankabo UA, Ertsen MW, van de Giesen N. The relations between farmers' land tenure security and agriculture production. An assessment in the perspective of smallholder farmers in Rwanda. Land Use Policy. 2022;118: 106122.
42. RWFA. Forest Investment Program for Rwanda. Kigali, Rwanda: Ministry of Lands and Forestry; 2017
43. Ihli H, Seegers R, Winter E, Chiputwa B, Gassner A. Preferences for tree fruit market attributes among smallholder farmers in Eastern Rwanda. Agric Econ. 2022;53(1):5–21.
44. Woldeyohanes T, Kegode H, Hughes K, Ouattara I, Vagen T-V, Winowiecke LA, et al. Regreening Africa Consolidated Endline Survey Report. Nairobi: World Agroforestry; 2023.
45. Cornelius JP, Miccolis A. Can market-based agroforestry germplasm supply systems meet the needs of forest landscape restoration? New For. 2018;49(4):457–69.
46. Hillbrand A, Borelli S, Conigliaro M, Olivier E. Agroforestry for landscape restoration: exploring the potential of agroforestry to enhance the sustainability and resilience of degraded landscapes. 2017.
47. El-Masri MM, Fox-Wasylyshyn SM. Missing data: an introductory conceptual overview for the novice researcher. Can J Nurs Res Arch. 2005;1:156–71.
48. Vaitla B, Coates J, Glaeser L, Hillbruner C, Biswal P, Maxwell D. The measurement of household food security: correlation and latent variable analysis of alternative indicators in a large multi-country dataset. Food Policy. 2017;68:193–205.
49. Wambogo EA, Ghattas H, Leonard KL, Sahyoun NR. Validity of the food insecurity experience scale for use in sub-Saharan Africa and characteristics of food-insecure individuals. Curr Dev Nutr. 2018;2(9):nzy062.
50. FAO. Methods for estimating comparable rates of food insecurity experienced by adults throughout the world. Rome, Italy. 2016.
51. Jubayer A, Islam S, Nowar A, Nayan MM, Islam MH. Validity of Food insecurity experience scale (FIES) for use in rural Bangladesh and prevalence and determinants of household food insecurity: an analysis of data from Bangladesh integrated household survey (BIHS) 2018–2019. Heliyon. 2023;9:6.
52. Cafiero C, Viviani S, Nord M. Food security measurement in a global context: the food insecurity experience scale. Measurement. 2018;116:146–52.
53. Smith MD, Kassa W, Winters P. Assessing food insecurity in Latin America and the Caribbean using FAO's food insecurity experience scale. Food Policy. 2017;71:48–61.
54. Matavel C, Hoffmann H, Rybak C, Steinke J, Sieber S, Müller K. Understanding the drivers of food security among agriculture-based households in Gurué District, Central Mozambique. Agric Food Secur. 2022;11(1):7.
55. Silvestri S, Sabine D, Patti K, Wiebke F, Maren R, Ianetta M, et al. Households and food security: lessons from food secure households in East Africa. Agric Food Secur. 2015;4:1–15.
56. Mango N, Zamasiya B, Makate C, Nyikahadzoi K, Siziba S. Factors influencing household food security among smallholder farmers in the Mudzi district of Zimbabwe. Dev South Afr. 2014;31(4):625–40.
57. Habtemariam LT, Gornott C, Hoffmann H, Sieber S. Farm production diversity and household dietary diversity: panel data evidence from rural households in Tanzania. Front Sustain Food Syst. 2021;5: 612341.
58. Mango N, Makate C, Mapemba L, Sopo M. The role of crop diversification in improving household food security in central Malawi. Agric Food Secur. 2018;7(1):1–10.
59. Bland JR, Cook AC. Random effects probit and logit: understanding predictions and marginal effects. Appl Econ Lett. 2019;26(2):116–23.
60. Jones KW, Lewis DJ. Estimating the counterfactual impact of conservation programs on land cover outcomes: the role of matching and panel regression techniques. PLoS ONE. 2015;10(10): e0141380.
61. Pham H-G, Chuah S-H, Feeny S. Factors affecting the adoption of sustainable agricultural practices: findings from panel data for Vietnam. Ecol Econ. 2021;184: 107000.
62. Ngoma H, Mulenga BP, Snyder J, Banda A, Chapoto A. Poverty and weather shocks: a panel data analysis of structural and stochastic poverty in Zambia. 2019.
63. Wooldridge JM. Econometric analysis of cross section and panel data: MIT press; 2010.
64. Gebre GG. Prevalence of household food insecurity in East Africa: linking food access with climate vulnerability. Clim Risk Manag. 2021;33: 100333.
65. Kitonga K, Jamora N, Smale M, Muchugi A. Use and benefits of tree germplasm from the World Agroforestry genebank for smallholder farmers in Kenya. Food Secur. 2020;12(5):993–1003.

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