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Contextual drivers of climate-smart agroforestry adoption in Bugesera and Rulindo agroecosystems of Rwanda

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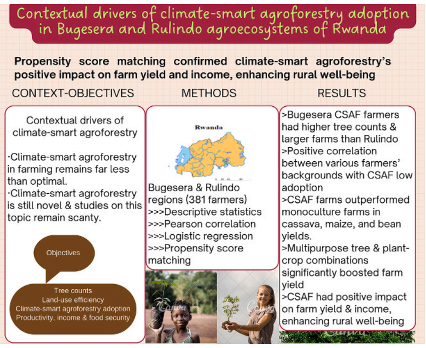
HIGHLIGHTS

- Climate-smart agroforestry in smallholder farming remains far less than optimal.
- Climate-smart agroforestry is still novel and studies on this topic remain scanty.
- Bugesera farmers had higher tree counts and larger farms than Rulindo.
- Multipurpose tree and plant-crop combinations significantly boosted farm yield.
- Propensity score matching proved climate-smart agroforestry uplifts rural well-being.

GRAPHICAL ABSTRACT



Contextual drivers of climate-smart agroforestry adoption in Bugesera and Rulindo agroecosystems of Rwanda

Propensity score matching confirmed climate-smart agroforestry's positive impact on farm yield and income, enhancing rural well-being

CONTEXT-OBJECTIVES

Contextual drivers of climate-smart agroforestry

·Climate-smart agroforestry in farming remains far less than optimal.
·Climate-smart agroforestry is still novel & studies on this topic remain scanty.

Objectives

Tree counts
Land-use efficiency
Climate-smart agroforestry adoption
Productivity, income & food security

METHODS

Bugesera & Rulindo regions (381 farmers)
>>>Descriptive statistics
>>>Pearson correlation
>>>Logistic regression
>>>Propensity score matching

RESULTS

>Bugesera CSAF farmers had higher tree counts & larger farms than Rulindo
>Positive correlation between various farmers' backgrounds with CSAF low adoption
>CSAF farms outperformed monoculture farms in cassava, maize, and bean yields.
>Multipurpose tree & plant-crop combinations significantly boosted farm yield
>CSAF had positive impact on farm yield & income, enhancing rural well-being

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ABSTRACT

This study examined 381 farmers from two regions in Rwanda to investigate how contextual factors at the field level interact with climate-smart agroforestry (CSAF) practices. Farmers were categorized as low (LAD), medium (MAD), and high (HAD) adopters based on tree counts. Various contextual factors — notably location, demographics, assets, farm characteristics, and institutional variables — were analyzed using descriptive statistics, Pearson correlation, logit regression, and propensity score matching. Farmers in Bugesera had larger farms and higher tree counts than those in Rulindo, resulting in greater farm income in Bugesera. Positive correlations were found among altitude, slope, erosion class, gender, household size, poverty level, income source, marital status, education, farm area, cropping practices, farm-river distance, changes in CSAF cover, population dynamics, and LAD. CSAF farms outperformed monoculture farms regarding cassava, maize, and bean yields, particularly in Bugesera and Rulindo among larger landholdings. Logit regression analysis showed that combinations of multipurpose trees and crop planting significantly improved farm yields, with household size and farm size being critical factors for CSAF adoption. Propensity score matching confirmed the positive effects of CSAF practices on farm yield and income, contributing to enhanced rural well-being. These findings underscore the crucial role of CSAF in promoting well-being. The results encourage stakeholders to develop strategies for CSAF. While these findings are specific to local contexts, they may hold potential relevance at regional and global levels. This

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evidence supports the development of government-led policies implemented through extension services to systematize and stabilize CSAF practices across diverse farming systems.

Practical implications

The pressing challenges of climate change entail forging climate-smart initiatives in farming to promote climate-resilient growth, such as transitioning to climate-smart agroforestry (CSAF) farming for agricultural sustainability and conservation efforts. Prioritizing CSAF in farming would deliver greater benefits regarding greenhouse gas emission reductions, forest preservation, biodiversity conservation, productivity, income, and food security.

Generally, CSAF represents climate change resilience and mitigation measures to improve tree cover, restore degraded land (contributing to erosion control and soil fertility), protect riverbanks, and enhance climate-resilient livelihoods. The wood from CSAF can provide various benefits, such as fruits, and can be logged for housing, firewood, wood charcoal, stakes for climbing crops, or fodder (Wijayanto et al., 2022). Results from this study indicate that multipurpose tree and plant-crop combination practices in CSAF farming significantly influence farm yield. Additionally, household size and farm size were the two most important household attributes influencing CSAF adoption. Increasingly, CSAF adoption positively and significantly impacts farm yield and income, which are proxies for well-being. This finding suggests that CSAF is instrumental in preserving the well-being of farmers in rural settings.

In particular households, farmers indicated that, besides fruits, fuelwood is the main by-product of CSAF pruning, thinning, and clearing (Jemal et al., 2018). Also, CSAF can contribute to drought mitigation in the eastern dry lowlands and floods in the wetlands of the highlands caused by torrential rains flowing from deforested hills and mountains (steep slopes) in the rest of the country (central, north, south, and west).

Case studies on CSAF are essential as they provide useful information for identifying factors contributing to and hindering adoption. Such studies also offer the opportunity to use scientific approaches to analyze and formulate recommendations on new farming skills, why some technologies fail, or why they seem to work in some contexts, but not in others. Since CSAF is still novel and studies on this topic are still rare, the current study provides insight into future comparisons of CSAF adoption in study areas or elsewhere with similar growers' backgrounds. CSAF is not given due consideration in national priorities. Hence, we recommend that CSAF be prioritized in budgets and policy formulations. Farmers should be motivated to adopt CSAF by organizing training and deploying extension agents, for example, explaining to them the benefits of CSAF, and subsidizing tree seedlings, especially in the early stage of CSAF adoption. Given the scale of poverty in rural areas, farmers mostly focus on seasonal crops rather than perennial crops. In this respect, CSAF adoption can be upscaled if the government and NGOs provide some financial incentives to the farmers.

As every region is unique in physical (natural environment) and human characteristics, there is no one-size-fits-all solution to challenges faced by rural populations. Farmers in the Rulindo highlands are farming on steep slopes, contending with issues of soil erosion and mining activities that leave open-pit mines unfilled. Concerted efforts should be made to develop terraces and plant trees alongside them (alley cropping) while filling the open-pit mines left after resource extraction, and planting trees to rejuvenate the soil (regenerative farming) for short-term and long-term impacts. Farmers in the Bugesera savannah lowlands are facing long periods of drought. In past years, natural forests in this region were systematically cleared for the production and supply of charcoal to the City of Kigali, rendering it treeless and semi-arid. Concerted efforts are needed to develop irrigation schemes and subsidize tree seedlings for farmers to contend with drought and increase and sustain production in this region, known as food insecure.

1. Introduction

Globally, the degradation of ecosystems is a pressing phenomenon that increasingly affects many different types of landscapes and habitats (Folke et al., 2004) and is often induced by multiple anthropogenic malpractices (Ellis, 2011). Natural resources are constantly at risk (Gerber et al., 2013; Veldkamp et al., 2017) due to pollutants and the overuse of chemicals on plants (Matson et al., 1997; Chen et al., 2011). Climate shocks (Kalnay and Cai, 2003) induce biodiversity degradation (Foley et al., 2011) and the depletion of arable soils suitable for food production (Tscharntke et al., 2012). Climate-smart agriculture (CSA) was introduced as a novel method to protect farming from the cascading effects of climate change (Campbell et al., 2014; Ntawuruhunga et al., 2023). It serves as a farming adaptation to climate change by enhancing farm productivity and economic returns, boosting environmental resilience, and reducing GHG emissions (Nciizah and Wakindiki, 2015). Climate-smart agroforestry (CSAF) is one such method that integrates trees into food crop systems to adapt to climate change (Garrity et al., 2010; Sida et al., 2018). CSAF aims to secure food and advance broader development goals (increasing yield, decreasing land degradation, protecting biodiversity, and mitigating GHG emissions) while addressing climate change.

In the wake of the Sustainable Development Goals (SDGs), CSAF has been recognized as a suitable land husbandry approach to support vulnerable farming systems with climate resilience practices and mitigation while maximizing output (Seruni et al., 2021). CSAF emerges as a key tool in CSA, which helps to make agriculture more resilient to the escalating effects of climate change. It evolved from the age-old farming practice of combining crops with trees (agroforestry) on the same farmland. CSAF is an AF "plus" or good (smart) AF practice. This paradigm shift in farming is considered affordable with low-input technology to increase farm productivity while ensuring sustainability (Leakey et al., 2012).

Garrity et al. (2010) and Glover et al. (2013) stressed that despite its economic and ecosystem benefits and an increasing interest in CSAF adoption and promotion, its uptake in smallholder farming in SSA remains far less than optimal. To cope with the multiple challenges of our time affecting food security, modern farming systems have extended their scope to accommodate techniques and methods that integrate trees for multiple utilities rather than for timber and bioenergy alone to meet food security needs under climate change (Glover et al., 2013).

The uptake and adoption of smarter practices within farming landscapes are ongoing, with challenging processes involving complex management approaches at a field scale. Contextual factors influence the uptake, adoption, and upscaling of climate-smart practices and innovations in smallholder farmers, conditioning farm returns. Although existing conceptual frameworks in applied science suggest that contextual factors interact, limited research describes how this interaction occurs in practice. To bridge this gap, this study identifies the interconnected patterns among contextual factors that influence the uptake of CSAF practices.

This study seeks to understand how contextual factors at a field scale connect with CSAF practices, yield, income, and food security in a cross-site comparative analysis. The specific objectives are: (i) to determine the cross-site comparison of tree density for each CSAF practice that leads to diversification and increase of yield, income, and food security, (ii) to determine the land-use efficiency and profitability of CSAF, (iii) to investigate the effects of farmers' backgrounds on CSAF adoption, and (iv) to determine the factors that contribute to the CSAF adoption, farm productivity, income, and food security.

In Rwanda, as in any other country in the tropical region, farming presents unique opportunities and challenges due to an unstable climate. It is characterized by subsistence farming with quasi-non-existent technologies. Even if previous studies have extensively searched for the role of biophysical and climatic conditions that influence agricultural productivity, as a novel approach to tackling climate change, a research gap exists to understand how contextual factors at a field scale connect with CSAF practices and influence yield, income, and food security. While the present study focuses on specific local contexts, the outcomes may hold potential relevance at regional and global levels.

2. Materials and methods

2.1. Study area

Rwanda remains a rural economy with mainly subsistence farming. The country's pressing challenge is overpopulation on fragile and eroded land, exacerbated by climate change (Republic of Rwanda, 2023). Considering their contrasting agroecological features, this study was carried out in the Bugesera and Rulindo regions: Bugesera is located in the eastern semi-arid savannah lowland zone, and Rulindo is in the upland temperate zone.

The lowland Bugesera is part of the eastern savannah semi-arid area between Latitude 1037′56″ S and 2013′9″ S and Longitude 29021′0″ E and 30018′0″ E. It has a surface area of 1337 sq km. The mean temperature is between 26 and 29 ∘C, mostly hot throughout the year with erratic rainfall. Its landscapes vary from 1100 to 1780 m above sea level. Its annual precipitations vary between 700–1100 mm. Bugesera is part of the drier plains in eastern Rwanda covered with savannah grasslands and scattered woody trees, notably acacia (Fig. 1).

Rulindo is in the high altitude zone between Latitude 1044′S and Longitude 29059′E. This agroecological zone is a highland area of rolling hills and mountainous landscapes. It has a surface area of 567 sq km. Its relief is formed of steep slopes with an elevation of 1470–2200 m above sea level. It accommodates perennial and seasonal crop farming on hillslopes and vegetables in valleys with woodlot trees of eucalyptus, some grevillea, and calliandra scattered on farmlands. The registered mean annual temperature is 19 °C, while the annual precipitation is 1243.3 mm (Fig. 1).

2.2. Sampling and data collection

This study employed a multi-stage stratified random sampling method to select the study zones, from which 381 farm households were sampled (Fig. 2). The first stage consisted of selecting study regions. We used the agroecological map of Rwanda divided into four major agroecological zones: the eastern plains, central plateau, highlands, and area surrounding Lake Kivu (Iiyama et al., 2018a). In this stage, we selected two zones (eastern plains and highlands) due to budget constraints, while considering also their climatic disparities. In the second stage, two districts were selected from the two agroecological zones, one from each, considering both heterogeneity and homogeneity in certain

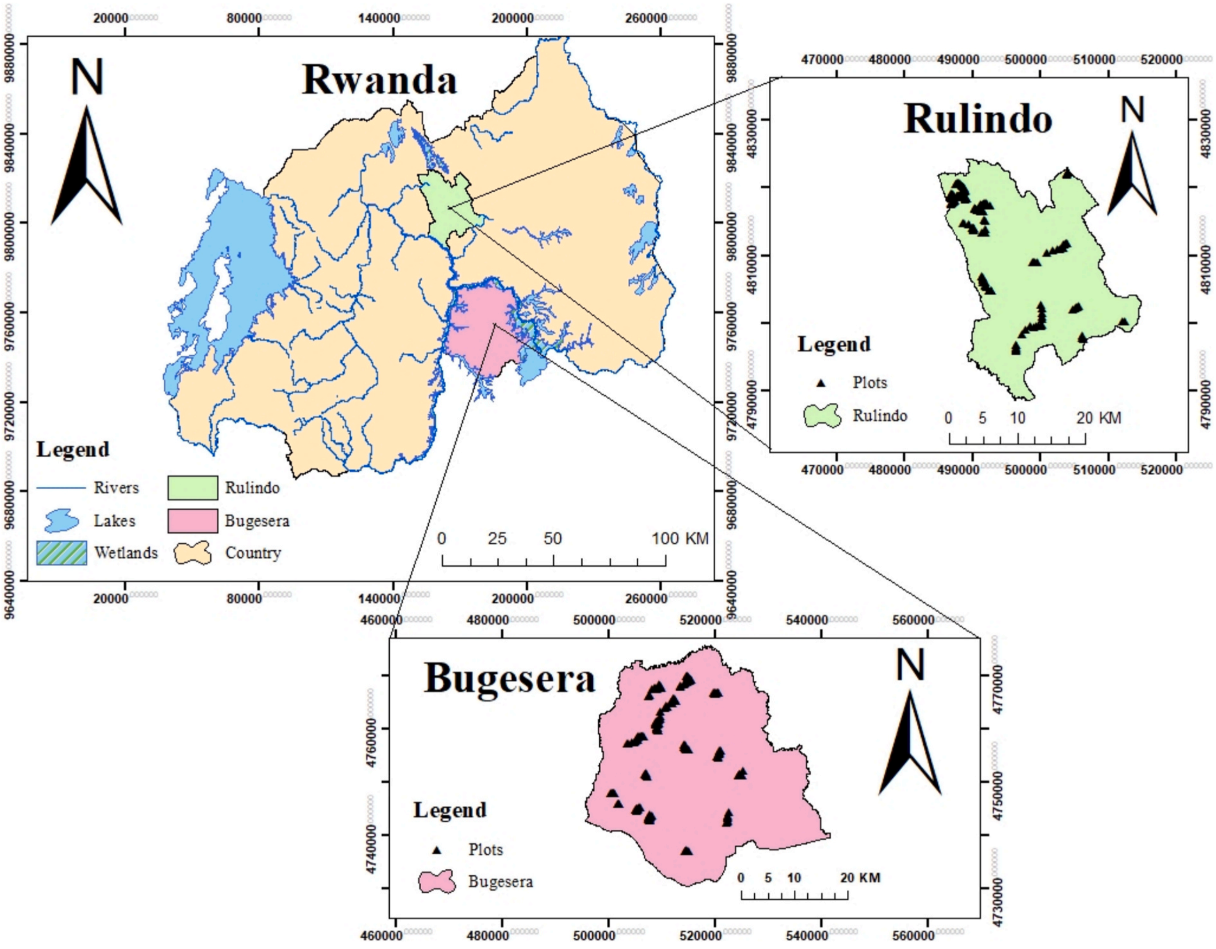

Fig. 1. Map of Rwanda with study areas (Bugesera and Rulindo) (adapted after CGIS).

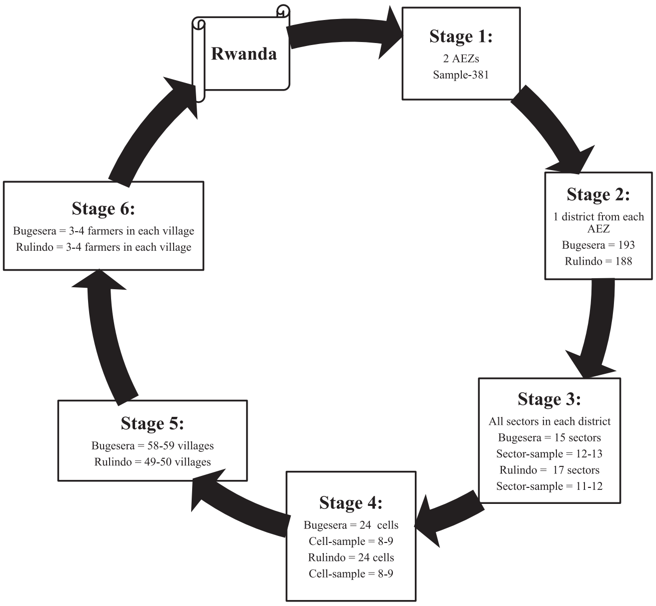

Fig. 2. Stages of sampling to select farm households in the study areas.

characteristics such as biophysical and climatic conditions, cropping patterns, water resources, and irrigation systems. In the third stage, all the sectors (sub-administrative entities) were selected from each district. In the fourth stage, we randomly selected 24 cells from each sector using stratified sampling. In this context, a cell serves as the fourth-level subdivision of Rwanda's local administrative structure. One cell may comprise several villages. In the fifth stage, fifty-eight to fifty-nine villages and forty-nine to fifty villages were randomly selected from each cell in Bugesera and Rulindo, respectively, using the Rwanda village statistics (NISR, 2023). In the sixth and last stage, about three to four farm households were randomly selected from each village in both study areas irrespective of their size of land holdings or farm. Using the Wonnacott and Wonnacott (1969) formula, a sample of 381 was obtained. This study used the data published from the Rwanda Agricultural Household Survey Report 2020 (NISR, 2021) to determine the sample size. 381 farm households were interviewed, comprising 193 from Bugesera and 188 from Rulindo. Before the study began, the questionnaire was pre-tested to improve survey quality and prevent the omission of important information necessary for achieving our research objectives. The questionnaire covered topics involving geospatial, climatic, demographic, and farm characteristics, as well as CSAF practices. In addition, the data on the Global Positioning System (GPS) coordinates were included in the survey. Face-to-face interviews with farmers were conducted on the farms. Informal agreements were made before the start of any session with the farm household by explaining the purpose and objectives of the study. Data were collected from farmers for their production season April to June 2023.

We interviewed household heads on their farms. Questions were asked in the local language (Kinyarwanda) and then translated into English for recording. For dependent variables, we asked farmers about the yield of CSAF in the previous season, forms of sale of woody materials from farms, consumed CSAF products share in households, sold CSAF products share on the market, the yield of food crops, consumed food crop share in households, sold food crops on the market, revenues from woody materials, revenues from food crops, revenues from livestock, off-farm income, and food security (in quantity and quality). For independent variables, we recorded information on agroecological zones, altitude, gender, age, civil status, education, household size, *ubudehe* (household poverty level), farm size, farming experience in CSAF, owning a radio, owning a mobile phone, livestock size, farm-river distance, training, extension visits, farmer knowledge, attitude, and motivation in CSAF adoption. Data were collected using a semi-structured questionnaire and personal observation in the field. In addition, we conducted three focus group discussions (FGDs), with 8–12 participants. The discussion sessions focused on the knowledge, attitude, and motivational factors that drive farmers to adopt CSAF practices. Also, interviews involved CSAF patterns and types of crops developed, and information on crops and CSAF income referring to each intercropped practice.

We also interviewed the local government (districts), ARCOS, and the model farmers to complement our findings. Two interviews were conducted with local officials (districts), one interview with an ARCOS staff member, and two model farmers. These officials were contacted to acquire an overview of CSAF practices in the study areas.

The observation technique was also used while collecting information in the field. Using a diary and camera, we documented what we observed in the field about CSAF practices. This approach allowed us to observe and describe the CSAF structures and compare farmers' utterances with our observations in the field (Castle et al., 2022). We observed the general farm conditions and farming practices, types of CSAF practices available, tree components and configuration, and slope and soil erosion control. We also gathered secondary data to complete the findings of this research. Secondary data were collected from various sources, notably peer-reviewed journal articles, published books, case studies, government policy documents, district development plans (DDPs), and grey literature. These data were collected to support, clarify, and interpret primary data.

2.3. *Data analysis*

Data were analyzed using Microsoft Excel, STATA Software, version 15 (Corp LLC, Texas, USA), and R software. The process involved four analysis levels: (i) cross-site comparison of tree density among the CSAF practices that lead to diversification and increase of yield, income, and food security (ii) land-use efficiency and profitability from CSAF (iii) effects of farmers' backgrounds on CSAF adoption, and (iv) factors that contribute to the CSAF adoption, farm productivity, income, and food security.

(i) *Cross-site comparison of tree density on farms for CSAF*

The number of trees on farms was compared between types of CSAF practices and between the two physiographic zones using a Kruskal-Wallis test, when Chi-square tests (Welham et al., 2004) were used to compare the proportions of farmers in their different food security categories. Three relative types of the number of trees on farms were constructed using tertiles in each sampled area:

1) Low CSAF adopters (LAD), defined as the 1st tertile of the farmers in terms of tree counts.
2) Medium CSAF adopters (MAD), defined as the 2nd tertile of the farmers in terms of tree counts, and
3) High CSAF adopters (HAD), defined as the 3rd tertile of the farmers in terms of tree counts.

Tukey's test in the Predict Means R package (Welham et al., 2004) was used for pairwise comparisons of different CSAF adoption levels between LAD, MAD, and HAD for each agroecology. Among the 381 farmers randomly selected to be included in the sample, some may not have land or trees, thus, these were removed to avoid bias in the analysis.

Food security analysis for the research participants in the study was ranked as follows:

- '1′ if they did not have enough food in their stock.
- '2′ if they had enough food but no dietary balance.
- '3′ if they had enough food in their diet.

In the analysis, scores 2 and 3 for the response variable ‘food security status’ were combined and considered as food-secure farming households (coded as 1) to signify farmers having at least access to food quantity that typically satisfies them within a month. These were compared to food-insecure households (coded as 0), weighted for those without access to food quantity that satisfies them within a month. ANOVA was used to compare contrasts and effects, while Chi-square tests were adopted to evaluate differences for their significant effects.

(ii) *Land-use efficiency and economic analysis of CSAF*

The land-use efficiency was determined using the Land Equivalent Ratio (LER) termed agronomic productivity, using the formula (Willey et al., 1983):

$$LER = \sum_{i=1}^{n} \frac{IY_i}{SY_i} \tag{1}$$

where n is the number of different crops intercropped, IY_i is the yield (kg.ha^{-1}) for the i^{th} crop under intercropping, and SY_i is the yield (ton. ha^{-1}) for the i^{th} crop under a monocropping (sole-cropping) production regime on the same farmland.

LER is the ratio of the area under monocropping (sole-cropping) to the area under intercropping needed to give equal amounts of yield (Mead & Willey, 1980) under the same management level. It is the total sum of the fractions of the intercropping yields over the monocropping yields. Monoculture systems are considered to have an LER value of 1, while an LER higher than 1 indicates higher productivity in polyculture systems (Sereke et al., 2015).

In our study, the LER was calculated for the combination of different crops in CSAF practices as follows:

$$LER = L_C + L_M + L_B = \frac{Y_C}{S_C} + \frac{Y_M}{S_M} + \frac{Y_B}{S_B} \tag{2}$$

where L_C, L_M, L_B are the LERs for the individual crops (cassava, maize, beans, respectively), Y_C, Y_M, Y_B are the individual crop yields (ton. ha−1) in CSAF, and S_C, S_M, S_B are their yields (kg.ha−1) in monocropping (monoculture).

Gross margins were computed to assess the income-return viability as follows (van Noordwijk, 2019). For annual crops, the gross margin was calculated as:

$$I = \sum (Y.P_Y) - (X_i.P_i) \tag{3}$$

I = income (Rwf.ha^{-1})Y = yield (kg.ha^{-1}).P_Y = unit price of yield (Rwf. kg.ha^{-1}).X_i = amount and type of input used in production ((i = seeds (cassava, maize, beans), fertilizers, pest control, labor, insurance).P_i = unit cost of i^{th} input.

The feasibility of cassava, maize, and beans under CSAF was analyzed using the Cost-Benefit ratio (B/C ratio):

$$B/Cratio = \frac{Income(I)}{Totalcost(C)} \tag{4}$$

(iii) Effect of CSAF practices and farmers’ backgrounds on farm yields

Two binary logistic regression models were used to test the effect of CSAF practices on farm yields (outputs) and the effects of farmers’ backgrounds on farm yields (outputs), respectively. The basic logit model formula is given by Gujarati (2004):

$$\begin{aligned} \mathrm{P}_i = \mathrm{P}rob(\Upsilon_i = 1) &= \frac{1}{1 + e^{-(\beta_0 + \beta_1 \mathrm{X}_{1i} + \ldots + \beta_k \mathrm{X}_{ki})}} \\ &= \frac{e^{(\beta_0 + \beta_1 \mathrm{X}_{1i} + \ldots + \beta_k \mathrm{X}_{ki})}}{1 + e^{-(\beta_0 + \beta_1 \mathrm{X}_{ii} + \ldots + \beta_k \mathrm{X}_{ki})}} \end{aligned} \tag{5}$$

Likewise,

$$\begin{aligned} \mathrm{P}_i = Prob(\Upsilon_i = 0) &= 1 - prob(\Upsilon_i = 1) \\ &= \frac{1}{1 + e^{(\beta_0 + \beta_1 \mathrm{X}_{1i} + \ldots + \beta_k \mathrm{X}_{ki})}} \end{aligned} \tag{6}$$

By dividing (5) by (6) we get,

$$\frac{Prob(\Upsilon_i = 1)}{Prob(\Upsilon_i = 0)} = \frac{\mathrm{P}_i}{1 - \mathrm{P}_i} = e^{(\beta_0 + \beta_1 \mathrm{X}_{1i} + \ldots + \beta_k \mathrm{X}_{ki})} \tag{7}$$

where, P_i is the probability that the farmer achieved high yields while $(1 - \mathrm{P}_i)$ is the probability that the farmer achieved low yields and e is the exponential constant.

After the computation of output scores (high yields as “*1*″ and low yields as “*0*”), a matrix of the number of “successes” and the number of “failures” was generated and used as the dependent variables, after which a regression analysis was performed using the generalized linear model of the binomial family with the logit link function to establish the relationships between the explained variables (Y_i) and explanatory variables (X_i) as follows:

(Model 1)

$$\begin{aligned} \Upsilon_i = \alpha + \beta_1 \mathrm{X}_{Taungya} + \beta_2 \mathrm{X}_{Homegarden} + \beta_3 \mathrm{X}_{Fallow} + \beta_4 \mathrm{X}_{Multipurpose\,trees} + \beta_5 \mathrm{X}_{Combination} \\ + \beta_6 \mathrm{X}_{Silvopastore} + \beta_7 \mathrm{X}_{Shelterbelts/windbreaks} + \beta_8 \mathrm{X}_{Alley} + \varepsilon_i \end{aligned} \tag{8}$$

$$\begin{aligned} (\mathrm{Model\,2})\ \mathrm{Y}j = \alpha + \beta_1 \mathrm{X}_{Age} + \beta_2 \mathrm{X}_{CivilStatus} + \beta_3 \mathrm{X}_{Educ} + \beta_4 \mathrm{X}_{HouseholdSize} \\ + \beta_5 \mathrm{X}_{Ubudehe} + \beta_6 \mathrm{X}_{FarmSize} + \beta_7 \mathrm{X}_{ExperienceCSAF} \\ + \beta_8 \mathrm{X}_{Training} + \beta_9 \mathrm{X}_{Extension} + \beta_{10} \mathrm{X}_{ErosionControl} + \varepsilon_i \end{aligned} \tag{9}$$

where Υ_i and Υ_j represent the binomial values of farm yields (the value 1 for high yields and 0 for low yields), $\beta_1, \ldots, \beta_{12}$ represent effect values, and ε is the error term.

(iv) *Effects of CSAF practices on farmers’ wellbeing.*

We used the propensity score matching (PSM) approach to estimate the impact of CSAF on farmers’ well-being (expressed on the proxy indicators of yield, income, and food security). This approach was selected for its ability to address the self-selection bias (Wijayanto et al., 2022). CSAF as a case study, the PSM approach estimates the impact of treatment by comparing the adopters and non-adopters with the same characteristics, using propensity score values from respondents (Rahman et al., 2021).

Propensity score matching (PSM) is a useful approach that accounts for the imbalance in covariates between the treated and comparison groups (untreated). The goal of propensity score estimation is to balance covariates between participants who received and did not receive treatment, making it easier to isolate the impact of treatment (Awe et al., 2020). Given a set of covariates (X), a propensity score $P(X_i)$ for a participant (i) is defined as the conditional probability (P) of assigning a participant to a particular treatment or control group (T), expressed thus (Rosenbaum and Rubin, 1983):

$$P(X_i) = (T_i = 1|X_i) \tag{10}$$

Practically, relevant pre-treatment variables are used to derive probabilities of group membership (Awe et al., 2020), which are then used to match participants in treatment and control groups such that both groups have equal means or likelihood of receiving treatment. Once matched, any differences between these two groups should reflect the true treatment effects in the study population and be comparable to the interpretation of randomized experiments. Independent variables likely to predict group membership should be identified and included in the propensity score matching estimation. This process does not limit the number of covariates used in this estimation. Once relevant covariates are identified, the probabilities of group membership (propensity scores) are computed for all the participants. The logistic regression model is the most commonly used regression technique (Guo and Fraser, 2009; Thoemmes and Kim, 2011) so that the predicted probabilities (P) of group membership (T) are the propensity scores $P(X_i)$ for a given set of covariates (X):

$$P(X_i) = (T_i = 1|X_i) = \frac{1}{1+e^{-X_i b_i}} \tag{11}$$

Therefore, this study adopted the PSM to determine the impact of CSAF practices on the well-being of farmers expressed on the proxy parameters of yield, income, and food security. Therefore, let $P(X) = Pr(z = 1|x)$ represent the probability of CSAF adoption by a farmer i.e. the propensity score. The PSM will then construct a statistical control group by matching observations on the CSAF adopters and non-adopter farmers for similar values of propensity scores. Rather than creating a match for adoption with the same value of X, we can instead match the probability of adoption.

To evaluate the impact of CSAF practices on farm productivity, income, and food security, a measure was used to compare the outcome of CSAF adopters and non-adopters. Let $Y_i =$ CSAF adopters;

$Y_0 =$ CSAF non-adopters.

Therefore, the impact of CSAF practices will be the change in mean outcome induced by the CSAF farming practices:

$$\overline{Y} = Y_1 - Y_0 \tag{12}$$

Since in Eq. (10), it is not directly possible to estimate individual treatment effects, the evaluation parameter, which is the Average Treatment Effect on the Treated (ATT), was computed to compare the different outcomes (yield, income, and food security) between adopter and non-adopter groups. The ATT formula is written as below (Becerril and Abdulai, 2010):

$$\begin{aligned} Y_{ATT} &= ATT(Y|X; Z = 1) = E(Y_1 - Y_0|, Z = 1) \\ &= E(Y_1|, Z = 1) - E(Y_0|, Z = 1) \end{aligned} \tag{13}$$

where Z is a parameter variable showing whether a respondent adopted CSAF practices or otherwise. It has a value of 1 if the respondent adopted CSAF and 0 if otherwise. Y_1 and Y_0 denote the wellbeing indicators of adopters and non-adopters and X denotes a vector of control variables.

In the PSM approach, the research variables are separated into three categories. The first category is the treatment variable, the CSAF adoption, measured by a dummy variable (1 if the farmers adopt CSAF, 0 otherwise). The second category is the control variables, such as age, civil status, education, household size, *ubudehe* (household poverty level), farm size, experience in CSAF, training, extension, and erosion control. The third category is the outcome variable, denoting the farmers' well-being (yield, income, and food security).

3. Results

3.1. CSAF farming in Bugesera and Rulindo regions

Fig. 3 portrays the agricultural land with a CSAF system [a] and another farming system without CSAF [b]. Maize planted under CSAF was luxuriant, while maize cropped in non-CSAF farming was exposed to heat stress and drought, resulting in poor harvests.

3.2. Description of site-level and socioeconomic factors influencing the adoption of CSAF

The description of farmers is presented in Table 1 with variables' measurement, mean, and standard deviation. The treatment variable, notably, CSAF adoption, has an average value of 0.438. Since this variable is a dummy, this suggests that less than half (44 %) of farmers adopted CSAF in their farms, while slightly more than half (56 %) did not (Fig. 4). CSAF integrates trees into crops such as *Persea Americana, Citrus sinensis*, *Grevilia robusta, Alnus spp, Calliandra calothyrsus,* and *Eucalyptus urophyla.* The main farm crops grown alongside these trees were beans, maize, Irish potatoes, and cassava. These crops are among the top priority crops (Kathiersan, 2012) in the inventory set forth by the government of Rwanda in its program implemented in 2008, termed 'farmland use consolidation' to promote market-oriented agriculture in the country, where subsistence farming is predominant.

The independent variable data shows that 23.8 % of surveyed farmers farmed on terraced land. Their average age was 43 years, while slightly above half were illiterate (56.6 %), which means not having finished elementary school education. Also, the average experience in CSAF was about 2 years, and more than three-quarters (76.3 %) rely on on-farm activities to earn their living. The average farm size was 1.088 ha. Regarding asset ownership, the results showed that more than three-quarters (77.6 %) of the participants live in mud-brick homes, 71.9 % own cell phones, and only 7 % have adopted irrigation on their farms. Regarding location, 50.6 % of the surveyed farmers lived in Bugesera and 49.4 % in Rulindo. The average yield was 608.171 kg.

The results presented in Table 2 show the difference in means of the variables used in the matching analyses and their significance levels. The significance levels indicate differences between CSAF adopters and


(a) (b)

Fig. 3. CSAF and non-CSAF farms in research locations: (a) CSAF farm in research locations; (b) non-CSAF farm in research locations.

Table 1
Descriptive statistics of selected variables.

Variable	Measurement	Mean	SD
Outcome variables			
CSAF	Dummy (farmer adopts = 1, otherwise = 0)	0.438	0.496
Yield	Continuous (kg-estimate from previous season)	608.171	3794.463
Income	Rwandan francs (Rwf)	9529.921	154,653
Expenditure	Rwandan francs (Rwf)	141.732	2766.504
Food stock	Dummy (food secure = 1, otherwise = 0)	0.892	0.310
Independent variables			
Location features			
AEZ	Dummy (Bugesera = 1, Rulindo = 0)	0.506	0.500
Altitude	Continuous (number of counts in meters)	1640	228.172
Farm position on slope	Dummy (up-slope = 1, otherwise = 0)	0.354	0.478
Erosion type	Dummy (rill = 1, otherwise = 0)	0.252	0.434
Erosion class	Dummy (high = 1, otherwise = 0)	0.094	0.292
Erosion control	Dummy (terraced = 1, otherwise = 0)	0.238	0.426
Demographics			
Gender	Dummy variable (male = 1, female = 0)	0.666	0.472
Age	Age of farmers in years	43.44	14.83
Civil status	Dummy variable (married = 1, not married = 0)	0.742	0.437
Education	Dummy variable (literate = 1, illiterate = 0)	0.566	0.496
Household size	Number of family members	4.052	1.863
"*Ubudehe*"	Dummy (high income = 1, low income = 0)	0.559	0.497
Main income source	Dummy (on-farm = 1, off-farm = 0)	0.763	0.685
Experience	Farming experience in years	2.493	3.294
Assets owned			
House type	Dummy (mud brick = 1, otherwise = 0)	0.776	0.416
Radio	Dummy variable (radio = 1, no = 0)	0.490	0.500
Mobile phone	Dummy variable (mobile phone = 1, no = 0)	0.719	0.450
Energy source	Dummy (fuelwood = 1, otherwise = 0	0.005	0.072
Irrigation	Dummy (yes = 1, no = 0)	0.070	0.256
Livestock	Number of cows owned	1.346	4.388
Farm characteristics			
Farm area	Continuous (farm area in ha)	1.088	1.408
Cropping practices	Dummy (pure stand = 1, intercropping = 0)	0.404	0.491
Farm-river distance	Dummy (<500 m, >500 m)	0.136	0.343
CSAF cover changes	Dummy (declined = 1, otherwise = 0)	0.047	0.212
Seedling source	Dummy (on-farm nurseries = 1, otherwise = 0)	0.147	0.354
Institutional variables			
Training	Dummy (yes = 1, no = 0)	0.144	0.351
Access to extension	Dummy (yes = 1, no = 0)	0.212	0.409
Population dynamics	Dummy (yes = 1, no = 0)	0.608	0.488

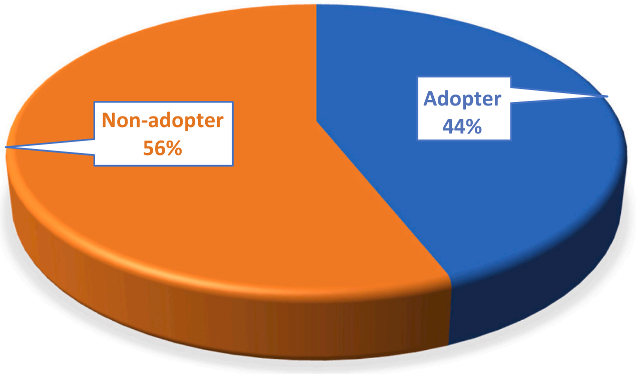

Fig. 4. Proportion of CSAF adopters and non-adopters.

Table 2
Mean differences in selected study variables.

Variable	Adopter	Non-adopter	Contrast	P>|t|
Outcome variables				
CSAF	0.445	0.430	0.014	0.773
Yield	836.384	430.079	406.305	0.300
Income	728,759	274931.8	453827.3	0.093***
Expenditure	145751.8	54986.36	90765.45	0.093***
Food stock	0.940	0.855	0.084	0.008*
Independent variables				
Location features				
AEZ	0.514	0.500	0.014	0.773
Altitude	1639.214	1641.03	−1.816	0.939
Farm position on slope	0.377	0.336	0.040	0.410
Erosion type	0.251	0.252	−0.000	0.985
Erosion class	0.041	0.135	−0.093	0.002***
Erosion control	0.275	0.210	0.065	0.140
Demographics				
Gender	0.700	0.640	0.060	0.216
Age	43.748	43.200	0.547	0.721
Civil status	0.760	0.728	0.031	0.486
Education	0.586	0.551	0.035	0.490
Household size	4.185	3.948	0.237	0.218
"*Ubudehe*"	0.604	0.523	0.081	0.113
Main income source	0.688	0.822	−0.133	0.059*
Experience	4.568	0.873	3.695	0.000***
Assets owned				
House type	0.694	0.841	−0.146	0.001***
Radio	0.538	0.453	0.085	0.098*
Mobile phone	0.838	0.626	0.212	0.000***
Energy source	0.005	0.004	0.001	0.861
Irrigation	0.137	0.018	0.119	0.000***
Livestock	1.329	1.359	−0.030	0.946
Farm characteristics				
Farm area	1.295	0.927	0.367	0.011**
Cropping practices				
Farm-river distance	0.137	0.135	0.002	0.950
CSAF cover changes	0.041	0.051	−0.009	0.666
Seedling source	0.113	0.172	−0.059	0.106
Institutional variables				
Training	0.227	0.079	0.148	0.000***
Access to extension	0.317	0.130	0.186	0.000***
Population dynamics	0.718	0.523	0.195	0.000***

Note: *, **, *** denote significance at 0.1, 0.05, and 0.01, respectively.

non-adopters concerning location-specific, demographic, asset ownership, farm-specific, institutional, and outcome variables.

The dataset contained 381 observations, with 44 % (167) of farmers adopting CSAF on their farms, while the remaining farmers did not integrate trees into their farming systems. Moreover, the study collected information on several variables: location, demographics, asset endowment, farm characteristics, institutional variables, CSAF adoption, farm yield, income, costs, and household food security. Results showed that CSAF adopters were better off than non-adopters, with higher annual income, greater expenditure, and improved food security. These differences in outcome variables were statistically significant at the 0.01 and 0.1 levels, respectively.

Similarly, the study revealed significant differences between CSAF adopters and non-adopters as predictor variables. The mean high erosion rate was 4.1 % among CSAF adopters, compared to 13.5 % among non-adopters. Additionally, 68.8 % of CSAF adopters reported relying on farming as the main income source, a higher proportion than non-adopters. The mean experience in CSAF practices was 4.5 years for adopters, compared to 3.7 years for non-adopters. CSAF adopters and non-adopters showed contrasting characteristics in erosion classification, the main source of income, farming experience, house type, radio, cell phone ownership, irrigation, farm area, training, access to extension services, and population dynamics (Table 2).

In many of the variables collected, we found that farmers adopting CSAF are better off than non-adopters. For example, CSAF adopters had larger farm incomes than non-adopters ($p < 0.1$). The outcome variable data also shows that the adopter farmers are more food secure than the non-adopter farmers ($p < 0.01$). However, the results cannot be a generalized impact of CSAF on farmers' subjective well-being because the comparison does not capture farmers' characteristics holistically.

3.3. Description of CSAF practices in study areas

The study on CSAF practices in study areas revealed that most of the interviewed farmers involve perennial woody species on crop farms. By adopting the classification of Nair (2019), the CSAF practices in study areas were home gardens (HG), alley cropping (AC), improved fallow (IF), multipurpose trees (MT), plantation-crop combination (PC), shelterbelts/windbreaks (SW), and silvopasture (SP). Taungya (TG), which originated in Asia (Nair, 2019) became successful at its introduction and was adopted by other countries, such as in Africa (Equatorial Africa) and Latin America. It refers to crops grown during the early stages of forest plantation establishment.

However, over the years, farmers have questioned the taungya practice because it grants no guarantees of tenure over land as participants keep shifting from one location in quest of new arable lands. Accordingly, a decline in taungya adoption was registered among farmers. An HG is a multispecies production system practiced around the homesteads. AC combines fast-growing, preferably leguminous woody species in single or grouped rows. IF refers to fast-growing, preferably leguminous woody species planted during the fallow phase of shifting cultivation. MT refers to fruit and other trees randomly or systematically planted in cropland or pasture to provide fruit, fuel wood, fodder, stakes for climbing crops, and timber, among other services, on farms and rangelands. PC integrates multistorey mixtures of trees and crops (such as coconut, cacao, coffee, and rubber) and shade trees and crops. SW refers to rows of trees around farms and fields planted and managed as part of crop or livestock operations to protect crops, animals, and soil from natural hazards, including wind, excessive rain, seawater, or floods. SP is a practice that combines trees with forage and livestock production, such as grazing in existing forests, using trees to create live fences around pasture, or providing shade and erosion control.

About 44 % of participant farmers adopt CSAF (Table 3). CSAF has been adopted by 23 % in Bugesera and 21 % in Rulindo. Using the Kruskal-Wallis test to compare the CSAF adoption across the two sites, the results showed that the mean adoption was likely to vary significantly across the two sites ($p < 0.10$).

3.4. Farmers' categorization in CSAF adoption

Farmers were categorized using tertiles (Table 4). P-values were estimated by applying the Kriskal-Wallis tests to compare levels of CSAF adoption: LAD for low adopters, MAD for medium adopters, and HAD for high adopters. The mean number of trees CSAF farmers grew was slightly higher in Bugesera (17 ± 107.14) agroecology than in Rulindo (16 ± 92.29). Again, the farm area per farmer was larger in Bugesera (1.69 ± 1.63 ha) agroecology compared to Rulindo (0.41 ± 0.36 ha). Farm size in the eastern semi-arid savannah lowland (Bugesera) was fourfold larger than in the temperate zone of the central highlands (Rulindo).

Table 3
Average CSAF practices for each study site.

AEZ	Yes	No	Total	Mean (±SD)
Bugesera	86(23 %)	107(28 %)	193(51 %)	44.56 (±14.84)
Rulindo	81(21 %)	107(28 %)	188(49 %)	43.09 (±18.38)
Total	167(44 %)	214(56 %)	381(100 %)	43.83 (±33.23)*
$\chi2 = 4.7059$, df = 2, $p = 0.09509$				

Table 4
Farmers' categorization in terms of CSAF adoption.

Land use	LAD	MAD	HAD	Mean (±SD)
No. of farmers				
Bugesera	185	4	4	
Rulindo	181	4	3	
Mean no. of trees				
Bugesera	4 ± 7.85	88 ± 14.46	366 ± 433.03	17 ± 107.14
Rulindo	6 ± 9.05	62 ± 6.65	535 ± 609.66	16 ± 92.29
Total land size (ha)				
Bugesera	0.44 ± 0.22	1.42 ± 0.48	4.68 ± 0.69	1.69 ± 1.63
Rulindo	0.41 ± 0.36	1.00 ± 0.00	1.5 ± 0.00	0.41 ± 0.36

3.5. Relationships among farmers' backgrounds and CSAF attributes

The correlation analysis between farmers' backgrounds and CSAF adoption classification (Table 5) showed an inverse relationship between erosion type and erosion class and the CSAF low adoption in Bugesera (rho = −0.038, rho = −0.02, respectively). In Rulindo, altitude, farm position on slope, and erosion class showed positive relationships with CSAF low adoption (rho = 0.05, rho = 0.05, rho = 0.02, respectively). Notwithstanding, the inverse relationship was found between farm position on slope and CSAF moderate adoption (rho = −0.03). There were no significant relationships between site characteristics and CSAF high adoption.

In Rulindo, positive correlations were disclosed between gender, household size, *ubudehe*, and the main income source and CSAF low adoption (rho = 0.0391, rho = 0.0012, rho = 0.0314, rho = 0.0305). At the same time, civil status displayed an inverse relationship (rho = −0.0738). Also, positive and inverse relationships were disclosed between the main income source and household size in medium CSAF adoption (rho = 0.0902, rho = −0.0301). In Bugesera, farmers' gender, civil status, education, and household size showed positive relationships with CSAF low adoption (rho = 0.0509, rho = 0.0646, rho = 0.0459, rho = 0.0451). Conversely, farmers' ages, *ubudehe*, and main income

Table 5
Site characteristics as a function of CSAF practice levels.

Agroecology	Site patterns	LAD	MAD	HAD
Bugesera	AEZ	1.00 ± 0.00[na]	1.00 ± 0.00[na]	1.00 ± 0.00[na]
	Altitude	1438.65 ± 48.43[ns]	1438.77 ± 35.50[ns]	1442.85 ± 82.61[ns]
	Farm position on slope	0.40 ± 0.49[ns]	0.50 ± 0.57[ns]	0.75 ± 0.50[ns]
	Erosion type	0.17 ± 0.37[b]	0.00 ± 0.00[na]	0.00 ± 0.00[na]
	Erosion class	0.13 ± 0.34[ns]	0.00 ± 0.00[na]	0.50 ± 0.57[ns]
	Erosion control	0.06 ± 0.24[b]	0.00 ± 0.00[na]	0.00 ± 0.00[na]
Rulindo	AEZ	0.00 ± 0.00[na]	0.00 ± 0.00[na]	0.00 ± 0.00[na]
	Altitude	1848.31 ± 136.05[c]	1799.00 ± 154.40[ns]	1837.14 ± 131.88[ns]
	Farm position on slope	0.29 ± 0.45[c]	0.25 ± 0.50[b]	0.33 ± 0.57[ns]
	Erosion type	0.33 ± 0.47[ns]	0.50 ± 0.57[ns]	0.33 ± 0.57[ns]
	Erosion class	0.04 ± 0.20[b]	0.00 ± 0.00[na]	0.33 ± 0.57[ns]
	Erosion control	0.41 ± 0.49[ns]	0.50 ± 0.57[ns]	0.66 ± 0.57[ns]

[b] significant correlation at $p < 0.05$; [c] significant correlation at $p < 0.1$; [ns] not significant; [na] not applicable.

source were negatively correlated with low CSAF adoption (rho = −0.0439, rho = −0.0004, rho = −0.0953). Also, CSAF medium adoption was positively and significantly associated with farmers' ages (rho = 0.0652). There were no significant relationships between farmers' demographics and CSAF high adoption (Table 6).

In Bugesera, farm area, cropping practices, farm-river distance, and CSAF cover changes showed positive correlations with CSAF low adoption (rho = 0.00, rho = 0.06, rho = 0.03, rho = 0.02, respectively). In contrast, seedling sources showed an inverse relationship with CSAF low adoption (rho = −0.00). Inversely, in Rulindo, inverse relationships were found between farm area, farm − river distance, and CSAF cover changes and CSAF low adoption (rho = −0.00, rho = −0.02, rho = −0.01, respectively). There were no significant relationships between farm characteristics and CSAF medium and high adoption (Table 7).

In the Bugesera region, a positive relationship was found between population dynamics and CSAF low adoption (rho = 0.07), while an inverse relationship was between training and CSAF low adoption (rho = −0.02). There were no significant relationships between institutional characteristics and CSAF medium and high adoption for both regions (Table 8). Specifically, in Rulindo, no relationship was shown between institutional factors and any of the three levels of CSAF adoption (LAD, MAD, HAD).

3.6. Land-use efficiency among cropping patterns in study areas

In this section, we evaluated different CSAF scenarios and computed the land equivalent ratio (LER) for scenarios in which CSAF was compared with growing each selected sole crop (monocropping).

Yields and LER of combining trees with cassava, maize, and beans at various farm categories are shown in Table 9. The LER values computed for yields of cassava, maize, and beans grown in CSAF show that large LERs occur in Bugesera, where landholding is relatively large (LER = 714.974), and the same trend also occurred in Rulindo for large and medium landholdings (LER = 155.5, 160.981), respectively. This is true because large farms are associated with crop diversification (polyculture farming), which improves farm productivity, household income, and food security.

Table 6
Farmers' demographics as a function of CSAF practice levels.

Agroecology	Demographics	LAD	MAD	HAD
Bugesera	Gender	0.68 ± 0.46[c]	0.75 ± 0.50[na]	1.00 ± 0.00[na]
	Age	41.79 ± 13.84[b]	45.00 ± 9.66[c]	47.75 ± 18.09[ns]
	Civil status	0.77 ± 0.42[c]	1.00 ± 0.00[na]	0.75 ± 0.50[ns]
	Education	0.37 ± 0.48[b]	1.00 ± 0.00[na]	0.25 ± 0.50[ns]
	Household size	4.01 ± 1.88[b]	5.50 ± 0.57[ns]	3.75 ± 1.50[ns]
	"*Ubudehe*"	0.62 ± 0.48[a]	1.00 ± 0.00[na]	0.75 ± 0.50[ns]
	Main income source	0.79 ± 0.87[c]	0.00 ± 0.00[na]	0.75 ± 0.50[ns]
	Experience in CSAF	2.46 ± 3.39[ns]	9.50 ± 3.00[ns]	6.00 ± 4.00[ns]
Rulindo	Gender	0.62 ± 0.48[b]	1.00 ± 0.00[na]	0.66 ± 0.57[ns]
	Age	44.96 ± 15.50[ns]	38.75 ± 27.94[ns]	51.66 ± 10.59[ns]
	Civil status	0.70 ± 0.45[c]	1.00 ± 0.00[na]	0.66 ± 0.57[ns]
	Education	0.75 ± 0.43[na]	0.75 ± 0.50[ns]	0.66 ± 0.57[ns]
	Household size	4.04 ± 1.89[a]	4.25 ± 0.50[b]	4.66 ± 1.15[ns]
	"*Ubudehe*"	0.47 ± 0.50[b]	0.75 ± 0.50[ns]	0.66 ± 0.57[ns]
	Main income source	0.75 ± 0.43[b]	0.75 ± 0.50[c]	0.66 ± 0.57[ns]
	Experience in CSAF	2.29 ± 2.99[ns]	2.25 ± 3.86[ns]	2.33 ± 2.51[ns]

[a] significant correlation at $p < 0.01$; [b] significant correlation at $p < 0.05$; [c] significant correlation at $p < 0.1$; [ns] not significant; [na] not applicable.

Table 7
Farm characteristics as a function of CSAF practice levels.

Agroecology	Farm characteristics	LAD	MAD	HAD
Bugesera	Farm area	1.45 ± 1.68[a]	2.32 ± 1.51[ns]	1.93 ± 2.71[ns]
	Cropping practices	0.41 ± 0.49[c]	0.25 ± 0.50[ns]	0.50 ± 0.57[ns]
	Farm-river distance	0.06 ± 0.24[b]	0.25 ± 0.50[ns]	0.25 ± 0.50[ns]
	CSAF cover changes	0.02 ± 0.16[b]	0.00 ± 0.00[na]	0.00 ± 0.00[na]
	Seedling source	0.18 ± 0.39[a]	0.00 ± 0.00[na]	0.75 ± 0.50[ns]
Rulindo	Farm area	0.66 ± 0.86[a]	0.72 ± 0.78[ns]	1.28 ± 1.49[ns]
	Cropping practices	0.39 ± 0.49[ns]	0.50 ± 0.57[ns]	1.00 ± 0.00[na]
	Farm-river distance	0.20 ± 0.40[b]	0.50 ± 0.57[ns]	0.33 ± 0.57[ns]
	CSAF cover changes	0.06 ± 0.25[b]	0.00 ± 0.00[na]	0.33 ± 0.57[ns]
	Seedling source	0.09 ± 0.29[ns]	0.00 ± 0.00[na]	0.33 ± 0.57[ns]

[a] significant correlation at $p < 0.01$; [b] significant correlation at $p < 0.05$; [c] significant correlation at $p < 0.1$; [ns] not significant; [na] not applicable.

Table 8
Institutional factors as a function of CSAF practice levels.

Agroecology	Institutional factors	LAD	MAD	HAD
Bugesera	Training	0.04 ± 0.19[b]	0.00 ± 0.00[na]	0.00 ± 0.00[na]
	Access to extension	0.10 ± 0.31[ns]	0.00 ± 0.00[na]	0.75 ± 0.50[ns]
	Population dynamics	0.78 ± 0.41[c]	1.00 ± 0.00[na]	1.00 ± 0.00[na]
Rulindo	Training	0.23 ± 0.42[ns]	0.50 ± 0.57[ns]	0.66 ± 0.57[ns]
	Access to extension	0.30 ± 0.46[ns]	0.75 ± 0.50[ns]	0.66 ± 0.57[ns]
	Population dynamics	0.41 ± 0.49[ns]	0.75 ± 0.50[ns]	0.66 ± 0.57[ns]

[b] significant correlation at $p < 0.05$; [c] significant correlation at $p < 0.1$; [ns] not significant; [na] not applicable.

3.7. Profitability analysis for CSAF

Table 10 shows the profitability analysis of cassava, maize, and beans grown in CSAF systems in the eastern semi-arid savannah lowland zone (Bugesera). Results showed that the income from cassava, maize, and beans grown in CSAF outweighed monoculture. The highest production cost was obtained on the seedlings of cassava grown in CSAF, representing more than 4/5 (83 %) of the total cost. Moreover, revenues from cassava, maize, and beans increase as yields increase. The lowest revenues were obtained from cassava monocropping, while the highest were from beans under CSAF systems. The most profitable crop was bean farming under CSAF, representing 1.2 times than the bean monocropping. This is explained by the highest profit (Rwf 447,228) from growing beans under CSAF.

Cost-benefit analysis is one approach to determining the income-return viability of CSAF. The cost-benefit (B/C) ratios of selected crops grown in monoculture and polyculture (CSAF) farming in the study area were also estimated. The lowest B/C ratio was obtained at cassava

Table 9
Yields and LERs of cassava, maize, and beans cropped among CSAF.

AEZ	Farmer's category	Yield (kg h^{-1})						LER			LER (total)
		Sole crop			**CSAF**						
		Cassava	**Maize**	**Beans**	**Cassava**	**Maize**	**Beans**	**Cassava**	**Maize**	**Beans**	
Bugesera	Small (<1ha)	6.757	2.082	3.471	49.591	60.560	24.876	7.339	29.077	7.166	43.583
	Medium (1–2 ha)	29.857	29.285	3.614	59.585	44	23.285	1.995	1.502	6.442	9.940
	Large (>2ha)	1.737	0.636	1.042	633.283	211.870	18.529	364.56	332.636	17.777	714.974
Rulindo	Small (<1ha)	76.719	218.413	150.462	38.816	88.302	87.054	0.505	0.404	0.578	1.488
	Medium (1–2 ha)	1.100	5.82	4.170	38.323	567.572	120.124	34.819	97.355	28.805	160.981
	Large (>2ha)	1.461	0	2.610	109.643	190.570	210.149	75		80.5	155.5

Table 10
Profitability analysis of cassava, maize, and beans grown in dry lowland Bugesera.

	Items	Monoculture farming			Polyculture farming (CSAF)		
		Cassava	**Maize**	**Beans**	**Cassava**	**Maize**	**Beans**
1	**Cost (Rwf)**						
	Seedlings	42,981	36,276	20,803	76,868	59,129	55,750
	Fertilizers	0	0	0	0	0	0
	Pest control	0	0	0	0	0	0
	Labor	17,192	14,510	1,444	15,373	11,825	31,507
	Insurance	0	0	0	0	0	0
	Total cost (Rwf)	**60,174**	**50,787**	**22,247**	**92,242**	**70,955**	**87,257**
2	**Yield (kg.ha^{-1})**						
a	*Cassava (kg.ha^{-1})*	*109.47*	–	–	*1,031.81*	–	–
	Cassava price (Rwf.kg^{-1})	500	–	–	500	–	–
	Cassava value (Rwf.ha^{-1})	54,735	–	–	515,905	–	–
b	*Maize (kg.ha^{-1})*	–	*375.61*	–	–	*1,239.84*	–
	Maize price (Rwf.kg^{-1})	–	250	–	–	250	–
	Maize value (Rwf.ha^{-1})	–	93,902	–	–	309,960	–
c	*Beans (kg.ha^{-1})*	–	–	*159.58*	–	–	*763.55*
	Bean price (Rwf.kg^{-1})	–	–	700	–	–	700
	Bean value (Rwf.ha^{-1})	–	–	111,706	–	–	534,485
3	**Total revenue (Rwf)**	**54,735**	**93,902**	**111,706**	**515,905**	**309,960**	**534,485**
4	**Gross benefit (Rwf)**	**−5,439**	**43,114**	**89,458**	**423,662**	**239,004**	**447,228**
5	**B/C ratio**	**−0.09**	**0.84**	**4.02**	**4.59**	**3.36**	**5.12**

monocropping for −0.09, while the highest B/C ratio was obtained at beans cropped in CSAF systems for 5.12.

Table 11 shows the profitability analysis of cassava, maize, and beans grown in CSAF systems in the temperate zone of the central highlands (Rulindo). Results showed that the income from cassava, maize, and beans grown in CSAF outweighed monoculture. The highest production cost was obtained at seedlings of bean monocropping, representing slightly more than half (55 %) of the total cost. Moreover, revenues from cassava, maize, and beans increase as yields increase. The lowest revenues were from maize monocropping, while the highest were from beans under CSAF systems. The most profitable crop was bean farming under CSAF, representing 2.3 times that of bean monocropping. This is explained by the highest profit (Rwf 180,785) from growing beans under CSAF.

Table 11
Profitability analysis of cassava, maize, and beans grown in highland Rulindo.

	Items	Monoculture farming			Polyculture farming (CSAF)		
		Cassava	**Maize**	**Beans**	**Cassava**	**Maize**	**Beans**
1	**Cost (Rwf)**						
	Seedlings	15,574	32,471	49,717	5,893	15,507	33,155
	Fertilizers	0	0	0	0	0	0
	Pest control	0	0	0	0	0	0
	Labor	12,459	25,976	39,774	2,946	7,753	16,577
	Insurance	0	0	0	0	0	0
	Total cost (Rwf)	**28,033**	**58,447**	**89,491**	**8,839**	**23,260**	**49,732**
2	**Yield (kg.ha^{-1})**						
a	*Cassava (kg.ha^{-1})*	*122.12*	–	–	*128.33*	–	–
	Cassava price (Rwf.kg^{-1})	500	–	–	500	–	–
	Cassava value (Rwf.ha^{-1})	61,060	–	–	64,165	–	–
b	*Maize (kg.ha^{-1})*	–	*364.88*	–	–	*484.75*	–
	Maize price (Rwf.kg^{-1})	–	250	–	–	250	–
	Maize value (Rwf.ha^{-1})	–	91,220	–	–	121,187	–
c	*Beans (kg.ha^{-1})*	–	–	*236.72*	–	–	*329.31*
	Bean price (Rwf.kg^{-1})	–	–	700	–	–	700
	Bean value (Rwf.ha^{-1})	–	–	165,704	–	–	230,517
3	**Total revenue (Rwf)**	**61,060**	**91,220**	**165,704**	**64,165**	**121,187**	**230,517**
4	**Gross benefit (Rwf)**	**33,027**	**32,773**	**76,213**	**55,326**	**97,927**	**180,785**
5	**B/C ratio**	**1.17**	**0.56**	**0.85**	**6.25**	**4.21**	**3.63**

The lowest B/C ratio was obtained at maize monocropping (0.56), while the highest B/C ratio was obtained at cassava cropped in CSAF systems (6.25).

3.8. *Effect of CSAF practices and farmers' characteristics on farm yields*

Factors associated with yield in CSAF farming were studied using binary logistic regression models. Two binary logistic regression models were estimated to identify the variables influencing the yield increase in CSAF farming. The models were performed after passing the model's goodness-of-fit (GOF) test.

Model 1 evaluated the association between CSAF practices and yield (Table 12). By employing a 5 % criterion of statistical significance, multipurpose tree and plant crop combination practices in CSAF farming significantly influenced yield at 1 % statistical significance.

The odds ratio for adopting a multipurpose tree practice in CSAF farming shows that – holding all other variables constant – this smart farming approach is 0.2 times more likely to increase yield than other CSAF practices (OR = 0.203, 95 % CI = 0.096–0.427, $p < 0.01$). This implies that adopting the multipurpose tree practice in CSAF improves farm productivity and yield.

The odds ratio for the plant-crop combination practice in CSAF farming shows that – ceteris paribus – farmers who adopted this technique are 0.2 times more likely to increase yield than other CSAF practices (OR = 0.262, 95 % CI = 0.100–0.688, $p < 0.01$).

Table 13 (model 2) represents the independent variables used in the logit regression models to create and predict the propensity scores for the matching algorithm. The selected independent variables included farmers' demographics (age, civil status, education, household size, *ubudehe*, experience in CSAF), farm characteristics (farm size, erosion control), and access to institutional services (training, extension). The logit regression result reveals the factors affecting farmers' decisions to adopt CSAF practices. Applying a 5 % criterion of statistical significance, results showed that the farmers' decisions to adopt CSAF practices are positively and significantly affected by household size and farm size (Table 13).

3.9. *Average treatment effect of CSAF adoption on farmers' household wellbeing*

The impact of CSAF practices on household well-being was estimated using propensity score matching (PSM). The findings in Table 14 suggest that CSAF farmers are generally better off than non-adopters vis-à-vis various livelihood indicators. Since the comparison of mean differences doesn't consider the effect of other farmer household characteristics, they may confuse the impact of CSAF on farmers' well-being with the influence of closely related determinants. In this regard, we used the PSM to control for bias and predict the determinants of CSAF adoption, thus evaluating the average treatment effects (ATT).

The outcome variables used to estimate the farmers' household well-being were CSAF practice, farm yield, household income, household expenditure, and the level of household food security. The results of the average treatment effect for the treated (ATT) from the different matching algorithms of the five outcome variables are portrayed in Table 14. The average treatment effect (ATE) of the treatment value was about −0.070 for the CSAF practice indicator (p < 0.01). The ATE of the treatment on a farmer randomly drawn from the farmer population is 275.56 kg of farm yield. This implies that CSAF adoption increased the farmers' farm yields by 275.56 kg, and the yields of the sampled farmers who adopted CSAF by 526.11 kg (p < 0.05). This finding confirms the *a priori* expectation that CSAF adoption may likely enhance farmers' farm productivity. Additionally, the ATT and ATE of income were found to be 192,564 Rwandan francs (USD 146.08) and 83,952 Rwandan francs (USD 63.68), respectively (p < 0.05). This result indicates that the mean income of farmer households has significantly increased due to CSAF adoption.

Table 12
Logistic regression analysis of the association between CSAF practices and yield.

Variable	OR	SE	Z	P>|z|	95 % CI of OR
Home gardens	0. 847	0.324	−0.43	0.667	0.400–1.796
Alley cropping	1.346	0.855	0.47	0.640	0.387–4.679
Improved fallow	1.517	0.850	0.74	0.457	0.506–4.550
Multipurpose trees	0.203	0.077	−4.20	0.000*	0.096–0.427
Plant-crop combination	0.262	0.129	−2.72	0.007*	0.100–0.688
Shelterbelts/windbreaks	1.378	0.634	0.70	0.485	0.559–3.398
Silvopasture	0.620	0.535	−0.55	0.580	0.114–3.370

OR = odd ratio, SE = standard error, CI = confidence interval
Wald chi2(7) = 146.99 Number of respondents = 381
Prob > chi2 = 0.0000 Log likelihood = −115.65725

*Significant at 0.01.

Table 13
Logit model of CSAF farmers (n = 381).

Variable	Coef.	Std. Err.	Z	P>|z|	95 % Conf. Interval
Age	0.002	0.008	0.24	0.807	−0.014–0.018
Civil status	0.395	0.306	1.29	0.196	−0.204–0.995
Education	−0.330	0.257	−1.28	0.199	−0.835–0.173
Household size	0.164	0.078	2.10	0.036**	0.010–0.318
Ubudehe	−0.062	0.257	−0.24	0.810	−0.567–0.443
Farm size	0.226	0.104	2.17	0.030**	0.021–0.430
Experience in CSAF	0.048	0.036	1.32	0.188	−0.023–0.120
Training	−0.033	0.464	−0.07	0.942	−0.943–0.876
Extension	0.351	0.389	0.90	0.367	−0.412–1.114
Erosion control	0.074	0.279	0.27	0.789	−0.473–0.623
_cons	−0.521	0.446	−1.17	0.242	−1.395–0.352

Number of participants = 381
LR chi2(10) = 29.44
Prob > chi2 = 0.0011
Pseudo R2 = 0.0607
Log likelihood = −227.79196

**Significant at 0.05.

4. Discussion

Results showed that the mean number of trees CSAF farmers grew was higher, and the farm area per farmer was larger in the eastern semi-arid savannah lowland of Bugesera than in the Rulindo highlands. Ndoli et al. (2021) reached a similar conclusion. They found that due to biophysical, climatic, and socioeconomic contrasts, the east semi-arid savannah lowland held larger mean farm sizes than the western Rwanda uplands. They stressed that households in the eastern lowlands hold relatively more land associated with high CSAF adopters (HAD) and high-crop income than medium adoption (MAD) and low adoption (LAD) farmers. They emphasized that the HAD households in the eastern lowlands were wealthier (with larger farms and higher overall income), making them more food secure than MAD and LAD. Conversely, in the rest of the country (with hilly topography), most households were food insecure due to small farm sizes (Ndoli et al., 2021). Nyadzi et al. (2003) and Oino and Mugure (2013) asserted that farmers with smaller farm sizes are less likely to adopt CSAF because of the fear that trees might interfere with crop performance due to competition (for light, water, and nutrients).

The correlation analysis between farmers' backgrounds and CSAF adoption showed that most variables were associated with the farmers' CSAF low adoption (LAD) level in the study areas. Positive associations were found between altitude, farm position on a slope, erosion class, farmers' gender, household size, *ubudehe*, main income source, civil status, education, farm area, cropping practices, farm-river distance, CSAF cover changes, population dynamics, and LAD. This may be attributed to the low adoption scale of CSAF associated with small landholdings where farmers rely on local knowledge with traditional

Table 14
Average treatment results.

Variable	Sample	Treated	Controls	Difference	S.E.	t	p>|t|
CSAF practice	Unmatched	0.460629921	0.393700787	0.066929134	0.053956904	1.24	0.216
	ATT	0.460629921	0.578740157	−0.118110236	0.080233527	−2.68	0.008*
	ATU	0.393700787	0.417322835	0.023622047			
	ATE			−0.070866142			
Yield	Unmatched	1284.12205	1008.16535	275.956693	302.108891	0.91	0.362
	ATT	1284.12205	758.003937	526.11811	416.862491	2.38	0.018**
	ATU	1008.16535	782.629921	−225.535433			
	ATE			275.566929			
Income	Unmatched	560449.016	476103.937	84345.0787	132090.406	0.64	0.524
	ATT	560449.016	367884.843	192564.173	191372.438	1.97	0.050**
	ATU	476103.937	342833.071	−133270.866			
	ATE			83952.4934			
Expenditure	Unmatched	118151.673	233820.152	−115668.479	78761.6387	−1.47	0.143
	ATT	118151.673	222766.448	−104614.775	154382.377	−1.61	0.107
	ATU	233820.152	115253.543	−118566.609			
	ATE			−109265.386			
Food stock	Unmatched	0.909448819	0.858267717	0.051181102	0.033664547	1.52	0.129
	ATT	0.909448819	0.933070866	−0.023622047	0.05528399	−0.99	0.324
	ATU	0.858267717	0.929133858	0.070866142			
	ATE			0.007874016			

*, **Significant at 001, and 0.05.

specialized farming techniques, mainly subsistence farming being the farmers' survival. This result implies that a deep analysis and understanding of these factors is crucial for improving CSAF adoption and addressing barriers to change. Conversely, Felton et al. (2023) found an opposite but complementary result that farmers most motivated by profit maximisation would be least interested in CSAF adoption, as tree-crop farming is typically viewed as an activity with a large opportunity cost.

This study found no direct relationship between the farmers' demographics and CSAF high adoption (HAP). This implies that most farmers were in the small landholding category. This finding corroborates Iiyama et al. (2018b), who reported that most farmers in Rwanda own small farms of less than 1 ha, deriving their livelihoods from subsistence farming. Another study by Gashu et al. (2025) in northern Ethiopia found mixed results. The study reported that factors such as factors such as farmer's sex, educational level, access to extension services, family size, soil fertility, farmland size, and slope of farmland were positively associated with high CSAF adoption; in contrast age, distance to farmland, land tenure, livestock size, farm experience, and market distance were not significant.

Results showed that by comparing CSAF with growing sole crop (monocropping) using land equivalent ratio (LER), yields of selected crops – cassava, maize, and beans – grown in CSAF showed that large LERs occurred in Bugesera, where landholding is relatively large. The same trend also occurred in Rulindo for large and medium landholdings. These results imply that, as indicated by LER calculations, the intercropping system (CSAF) is more efficient in utilizing land resources, requiring less land area to produce the same yield as monocropping. These three crops were selected from other crops because they are among the priority crops listed by the government of Rwanda and implemented in its Crop Intensification Program (CIP). Concurrently, Scordia et al. (2023) found that, even in the event of harvest shortages in CSAF, trees may diversify and increase overall productivity, reducing farmers' vulnerability to markets.

Total yields in CSAF farms were higher than those in sole crop cassava, maize, and beans (Rustiana et al., 2021). These results concur with Musokwa (2019), who used the LER in evaluating maize grown with pigeon peas (LER > 1) and found that farming with trees on farmland generated higher yields than monocropping. A study in Eswatini found parallel results (Edje, 2014) that intercropping maize with pigeon peas produced higher yields than either crop in monoculture. In Benue State (Nigeria), a study by Egbe (2010) found similar results for sorghum/pigeon pea intercropping. CSAF adoption is key to saving the shortage of arable land, rather than monoculture. CSAF practices involving cassava, maize, and beans save a substantial area of land, which can eventually be devoted to other farm activities (Musokwa, 2019). Cassava, maize, and bean production under CSAF are recommended because of their higher LER and the combined yield of cereals, tubers, and leguminous crops for human consumption, livestock feeding, and biomass.

Results showed an increase in the income of cassava, maize, and beans grown in CSAF compared to monoculture in both study areas (Bugesera and Rulindo). Moreover, revenues from cassava, maize, and bean yields increased as yields increased (Rustiana et al., 2021). The most profitable crop was bean farming under CSAF in Bugesera and Rulindo, representing 1.2 times and 2.3 times that of bean monocropping. Bucagu et al. (2013) and Beedy et al. (2013) found that, though dependent on landholding size, CSAF practices may become more profitable if livestock is not overlooked in this process.

Results showed that multipurpose tree and plant-crop combination practices in CSAF farming significantly influenced farm yield. The odds ratio for adopting a multipurpose tree practice in CSAF farming shows that – holding all other variables constant – this practice is 0.2 times more likely to increase yield than other CSAF practices. This implies that adopting the multipurpose tree practice in CSAF improves farm productivity and yields. In a multiple-output land-use system, multipurpose trees are farmed and managed for multiple uses, products, or services. For Misele (2007), multipurpose trees are grown to serve manifold, useful and valuable purposes such as food, timber, fodder, poles, fuelwood, tutors for climbing crops, and environmental resources (soil fertility and windbreaks), and innumerable products (Tesfaye et al., 2010; Negash et al., 2012; Abreha and Gebrekidan, 2014; Girmay et al., 2015; Gebrewahid et al., 2019; Negese and Motuma, 2021).

The odds ratio for the plant-crop combination practice in CSAF farming showed that, holding other factors constant, farmers who adopted this practice were 0.2 times more likely to increase yields than farmers who adopted other CSAF practices. A similar study by Erin et al. (2016) reported that CSAF transformed degraded lands into fertile soils in SSA by increasing tree densities (for example, Mali, Ethiopia, Burkina Faso, Malawi, and Senegal), which has induced higher yields.

Among the selected independent variables of farmers' demographics (age, civil status, education, household size, *ubudehe*, experience in CSAF), farm characteristics (farm size, erosion control), and access to institutional services (training, extension) to predict the factors affecting farmers' decision to adopt CSAF practices, household size, and farm size were two most important household attributes which were statistically significant ($p < 0.5$). This implies that larger households are more likely to adopt CSAF than small-sized families because CSAF is labor-intensive. Hence, larger households have more labor force (parents and children) to work on farms and expect higher returns from higher CSAF adoption (Khandagale et al., 2012). The positive and significant association between household size and CSAF adoption underscores this postulate. Farmers with large farms possess economic advantages to expand and diversify their assets (Jamala et al., 2013) and more scope and opportunities for CSAF adoption (Kabwe et al., 2009).

Using the propensity score matching (PSM), results revealed that CSAF adoption increased the farmers' farm yields by 275.56 kg, and the yields of the sampled farmers who adopted CSAF by 526.11 kg ($p < 0.05$). This finding confirms the *a priori* expectation that CSAF adoption may likely enhance farmers' farm productivity. Additionally, the ATT and ATE of income were found to be 192,564 Rwandan francs (USD 146.08) and 83,952 Rwandan francs (USD 63.68), respectively ($p < 0.05$), which suggests that the mean income of farmer households has significantly increased due to CSAF adoption. These results confirm our research hypothesis that CSAF farming improves farmers' well-being. Through CSAF farming, farmers improve and diversify farm output and income (Degrande et al., 2006; Kiptot et al., 2014). CSAF sustains farm productivity while safeguarding ecosystems (Franzen and Borgerhoff Mulder, 2007; Cerda et al., 2014).

This study provides valuable insights into the interactions between contextual factors influencing the adoption of CSAF as an alternative land-use option in the Bugesera and Rulindo agroecosystems. Overall, the findings of this study complement previous studies on the association and impact of various contextual factors in CSAF on farm productivity, income, and food security. Therefore, this study is not solely relevant to the rural landscapes of Rwanda but also other countries with similar contextual backgrounds.

5. Conclusion

This study analyzed contextual factors at a field scale and how they connect with CSAF practices, yield, income, and food security. The specific objectives were: (i) to determine the cross-site comparison of tree density for each CSAF practice that leads to diversification and increase of yield, income, and food security, (ii) to determine the land-use efficiency and profitability of CSAF, (iii) to investigate the effects of farmers' backgrounds on CSAF adoption, and (iv) to determine the factors that contribute to the CSAF adoption, farm productivity, income, and food security.

The cross-sectional data were collected from 381 farmer populations in the Bugesera and Rulindo regions. Three statistical approaches were used: Pearson correlation, binary logit regression, and propensity score matching (PSM). Findings from the Pearson correlation indicate that most variables were associated with the farmers' CSAF low-adoption (LAD) level in the study areas. Positive associations were found between altitude, farm position on a slope, erosion class, farmers' gender, household size, *ubudehe*, main income source, civil status, education, farm area, cropping practices, farm-river distance, CSAF cover changes, population dynamics, and LAD.

For the productivity comparisons of cropping patterns in study areas, results showed that by comparing CSAF with growing sole crop (monocropping) using land equivalent ratio (LER), yields of selected crops – cassava, maize, and beans – grown in CSAF showed that large LERs occurred in Bugesera where landholding is relatively large. The same trend also occurred in Rulindo for large and medium landholdings. Total yields in CSAF farms were higher than those in sole crop cassava, maize, and beans.

Results from the logit regression indicate that multipurpose tree and plant-crop combination practices in CSAF farming significantly influenced farm yield. Also, household size and farm size were the two most important household attributes influencing CSAF adoption. The results from PSM reveal that CSAF adoption has a positive and significant impact on farm yield and income, which are proxies of well-being. This finding suggests that CSAF is instrumental in preserving farmers' well-being, especially in rural areas reliant on rainfed subsistence farming.

One limitation of this study is that the data are cross-sectional and might not correctly capture farmers' characteristics and decisions in response to their adoption of CSAF, yields, costs, and prices due to price fluctuations on the market in a cross-site comparative study. However, recognizing the study's limitations, further research is encouraged to explore additional factors influencing the adoption and promotion of innovative, climate-smart farming practices, offering insights for more effective strategies.

Ethical statements

This study was reviewed and approved by Professor Maulid W. Mwatawala, the Vice-Chancellor of Sokoine University of Agriculture, on behalf of the Tanzania Commission of Science and Technology [approval number: SUA/ADM/R.1/8/851, dated 16th March 2022]. Approvals from district mayors were received before fieldwork was undertaken, and informed consent was obtained from all participants in the study. All information was confidential and used for research purposes only. Anonymity was maintained using coded identifiers during analysis to guarantee all personal information would stay private.

CRediT authorship contribution statement

Donatien Ntawuruhunga: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Edwin Estomii Ngowi:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Data curation. **Halima Omari Mangi:** Writing – review & editing, Visualization, Validation, Supervision, Data curation. **Raymond John Salanga:** Writing – review & editing, Visualization, Validation, Supervision, Project administration. **Kenneth Lynch Leonard:** Writing – review & editing, Visualization, Validation, Supervision, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data of this study will be available from the corresponding author upon reasonable request. However, it is not publicly open as it compromises the privacy of individual households, which we promised to protect during the face-to-face interview.

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