



Assessing climate-smart agroforestry practices: a study of tree species composition, distribution, and utilities in two contrasting agroecosystems of Rwanda

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Received: 24 December 2023 / Accepted: 22 August 2024
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Abstract Tree adoption on farms has expanded around the world in the last years due to food security concerns and is expected to further spread due to climate change. Climate-smart agroforestry (CSAF), a smart farming approach, is one of these farming patterns. In this study, we (a) analyzed the distribution and composition of trees in CSAF systems, (b) assessed tree diversity in CSAF systems, (c) analyzed CSAF best management practices, and (d) evaluated CSAF-derived utilities in two contrasting agroecological zones of Rwanda. In particular, species composition, diversity, richness, evenness, and similarity were estimated across land use types. Utility data were recorded as fulfilled goals from different practices.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10457-024-01063-x>.

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Home gardens, alley cropping, improved fallow, multipurpose trees, plantation crop combination, shelterbelts/windbreaks, and silvopasture are the predominant CSAF practices in Bugesera and Rulindo with different structures and compositions. Results highlighted that tree species diversity, richness, dominance, and importance decrease from Rulindo to Bugesera ($H' = 1.397\text{--}1.247$), ($D_{mg} = 0.621\text{--}0.368$), ($D = 0.192\text{--}0.117$), ($IVI = 58.42\text{--}58.02$). Moreover, farmers seemed to give more weight to utilities from goods meant for household survival such as fruits (home consumption), fuelwood (culinary), fodder (cattle-housed for zero-grazing), and standing trees (stakes for climbing crops). Logs, and poles/timber meant for commercial purposes were given the least weight. Introducing and upscaling fruit tree species on farms can be one of the best alternatives to improve local climate-resilient landscapes and livelihoods. The outcomes of this study can support the targeting of agricultural interventions and innovations in resource-poor settings struggling with food security challenges.

Keywords Smart farming · Climate resilience · Adoption · Food security · Management practices · Rwanda

Introduction

Tree-based farming, a prominent land-use system globally (Mukundente et al. 2020), has witnessed increasing challenges due to climate change that led to land degradation, and the destruction of biodiversity and ecosystems. These malevolent events are key contributors to global food shortages, particularly in resource-poor countries. In response to the climate crisis, innovative farming practices, such as climate-smart agroforestry (CSAF), have been developed to enhance agricultural productivity while coping with the adverse effects of climate change. Introduced as an evolution of traditional tree-on-farm farming practices (agroforestry), CSAF addresses environmental concerns, productivity issues, and the growing threat of global warming (Ntawuruhunga et al. 2023a, b). Consequently, CSAF represents a novel approach that integrates trees with crops, providing a dual benefit of increased agricultural productivity and resilience against climate change.

CSAF has emerged as a novel and vibrant research field and development over the last 20 years in the wake of the Millennium Development Goals (MDGs) and its continuation with the current Global Goals (SDGs). The CSAF concept emerged from the earlier farming approach termed agroforestry (AF) which focuses on combining crops, trees, and livestock at the farm level (Van Noordwijk et al. 2018) to diversify farm commodities and supply to households. Revolutionizing AF to climate change, the new farming approach—CSAF—is taking shape. It incorporates trees among crops to diversify and optimize farm utilities, and production and safeguard the environment while tackling climate change (van Noordwijk 2020).

Introduced as an evolution of traditional tree-on-farm farming practices (agroforestry), CSAF addresses environmental concerns, productivity issues, and the growing threat of global warming (Ntawuruhunga et al. 2023a, b). Consequently, CSAF represents a novel approach that integrates trees with crops, providing a dual benefit of increased agricultural productivity and resilience against climate change. CSAF is a new farming approach that evolved from the age-old farming practice of combining crops with trees (agroforestry) on the same farmland while addressing climate change challenges. This smart farming approach is considered an affordable,

low-input technology, scientifically demonstrated to increase farm productivity while ensuring sustainability in SSA (Garrity 2012). In their report, (UNDP 2016) emphasized that adverse impacts of climate change undermine countries' ability to achieve sustainable development. Accordingly, FAO inaugurated a new farming approach to conservation agriculture termed "climate-smart agriculture"—a unified approach to improve food production while coping with the adverse effects of climate change. Therefore, CSAF is one "climate-smart agriculture" added approach as a joint effort to improve agricultural production to meet the needs of the world population, degrading arable lands, and biodiversity (Ntawuruhunga et al. 2023a, b). In light of the Sustainable Development Goals (SDGs), CSAF has been heralded as a suitable land husbandry farming to support rural livelihoods, climate resilience, and mitigation while maximizing output and coping with risk (Seruni et al. 2021). CSAF as sustainable land stewardship can be one of the solutions to food insecurity, biodiversity loss, and environmental and ecosystem degradation. Gradually, CSAF is receiving increasing attention from researchers as a sustainable land management option because of its ecological, climate resilience, economic, and social attributes (Ndoli et al. 2021). (Ndomba, O.A., Bakengesa, S., Petro, R., Maguzu, J., Chamshama, S.A.O., Kiimu, H.R., Lema, M., 2015).

CSAF practices offer various advantages, including the cultivation of fast-growing fuelwood trees, native and exotic fruit trees that contribute to nutrition and income, and trees that curb soil erosion, and landslides, enhance organic fertilization, and provide medicinal products (Molua 2005). Under the new realities of climate change, CSAFs are multi-resource land use practices (Perfecto et al. 2005), that create new landscape elements to support and conserve biodiversity—at the species level and landscape level, regulate pests and diseases, and can efficiently adapt to changing socioeconomic conditions, ecological conditions, household needs, and marketing opportunities (ibid.). Amidst the challenging climate, there is a growing interest in exploring CSAF's potential to cultivate productive lands, and healthy ecosystems (USDA 2014), mitigate climate stresses, and promote sustainable food chains, thereby enhancing agroecosystem resilience and a food-secure environment (Chedzoy and Smalldge 2011).

According to FAO et al. (2023), reducing hunger remains a challenge, especially in the African subregions. Hunger and malnutrition keep rising across Africa. Compared to the rest of the world, Africa suffers the most with the largest proportion of the population affected by hunger: nearly 20% compared with 8.5% in Asia, 6.5% in Latin America and the Caribbean, and 7% in Oceania (FAO et al. 2023). Compared to the year 2021, hunger increased throughout all the subregions of Africa in 2022, where in SSA hunger increased from 22.2% to 22.5%, which reflects 9 million more people compared to 2021 (FAO et al. 2023). In SSA, small-scale farmers in SSA are particularly vulnerable to the uncontrollable, interconnected crises of climate, food, land degradation, and regulations on land use (CIFOR-ICRAF 2022). Smart farming approaches which involve intercropping, mulching, CSAF, and cattle-housed systems, present viable solutions to address these challenges by enhancing both productivity and resilience (CIFOR-ICRAF 2022).

In Rwanda, arable land is almost scarce given its small size and geomorphologic formation characteristics: the landscape is typically diverse with different disparities of slopes (Ntawuruhunga et al. 2023a, b). Additionally, competition for land (already highly fragmented due to population pressure) and water in suited habitable areas (lowland zones) and poor land management, are adding pressure on agricultural resources. Despite Rwanda's small size (26,338 square km), forests cover a substantial portion of the country's land, with 30.4% (724,695 ha) designated for forests. This includes 53.5% plantations, 18.1% natural mountain rainforests, 22.3% wooded savannah, and 6.1% shrubs (Republic of Rwanda, 2019). Notably, in Bugesera, forests cover 17.5% of the land (21,479 ha), while in Rulindo, forests cover 26% (14,729 ha). Despite these figures on forest cover, statistics on trees outside forests, specifically on-farm trees—CSAF, are absent from national records. This information gap raises concerns about the integration of CSAF into measurement, reporting, and verification systems of national statistics as well as reporting under the United Nations Framework Convention on Climate Change (UNFCCC). Consequently, a substantial gap exists between Rwanda's national ambitions and its ability to measure and report on the extent of CSAF (Rosenstock et al. 2019).

The promising CSAF technologies' low adoption rates in the context of climate change are a notable hindrance to sustainable farming in Rwanda. It is witnessed that infertile and degraded soils are continuously used and overexploited with insufficient replenishment. To curb these constraints in rural areas more is needed in participatory, innovative approaches that associate development stakeholders from the public, academia, industry, smallholder farmers, and local communities, to adopt context-adapted, proven, and appropriate climate-resilient farming approaches. CSAF is a new approach to enhancing access to and use of tree-based climate-smart technologies (improved tree seeds/seedlings) through effective scaling up of climate-smart technologies (improved technologies and management practices) that are already developed, proven, and in place to build resilience of farming systems and improve food security.

Having evolved as a new concept for the age-old farming practice (agroforestry), CSAF constitutes a novice in modern farming. The challenge remains linking knowledge, and action in CSAF research, education, and capacity development (Ntawuruhunga et al. 2023a, b). CSAF has not yet been fully established in academic and research curricula to provide a more holistic understanding of CSAF endorsed by scientific research evidence to sustain efficient, cost-effective land productivity. Moreover, despite the potential of CSAF to contribute towards soil regeneration and protection, conservation, economic returns, climate mitigation and adaptation, and food security, empirical studies on this topic are scanty. For instance, almost all previous studies in the last decades focused on combining trees with crops for ecosystem services, with less emphasis on their effects on income returns, food security, and climate mitigation and adaptation.

The absence of baseline data on tree diversity, composition, and distribution in CSAF systems in Bugesera—of dry climatic conditions—and Rulindo—of the temperate zone in highlands (soils highly erodible), necessitates further investigation for conservation efforts, sustainable ecosystem management, and coping with climate risks, food insecurity and poverty. This study aims to (a) analyze the distribution and composition of trees in CSAF systems, (b) assess tree diversity in CSAF systems, (c) analyze CSAF best management practices, and (d) evaluate CSAF derived utilities through a cross-site

comparative study. Specifically, this study identifies whether, (i) CSAF tree cover on farms differs at scale in a cross-site comparative analysis, (ii) enrichment planting with CSAF tree species that have high economic value is necessary, (iii) implementation of CSAF best management practices are necessary to promote multiple productive, protective and management outcomes, and (iv) variation in form and purpose support the benefits for smallholders in multiple ways. To answer these questions, we used household survey data from both the semi-arid lowlands and temperate zones of highlands agroecosystems in Rwanda.

Materials and methods

Study areas

This study was carried out in the household farming systems of Bugesera and Rulindo, Rwanda from April to June 2023. Bugesera is located in the eastern dry savannah lowland of the country (Fig. 1) between Latitude $1^{\circ}37'56''$ S and $2^{\circ}13'9''$ S and Longitude $29^{\circ}21'0''$ E and $30^{\circ}18'0''$ E. Bugesera's relief shows a succession of undulating hills, dry valleys, and some marshes due to tectonic collapse (Itegere 2016). The area is prone to severe drought spells, higher average temperatures (above the national average), and poor precipitations, which sometimes lead to famine and hunger (Twinomugisha 2013). Since the late 1990s, Bugesera has suffered long recurring droughts, and rainfall shortages followed by famines (Itegere 2016).

Rulindo study area is located in the temperate zone of the central highlands of Rwanda (Fig. 1) between

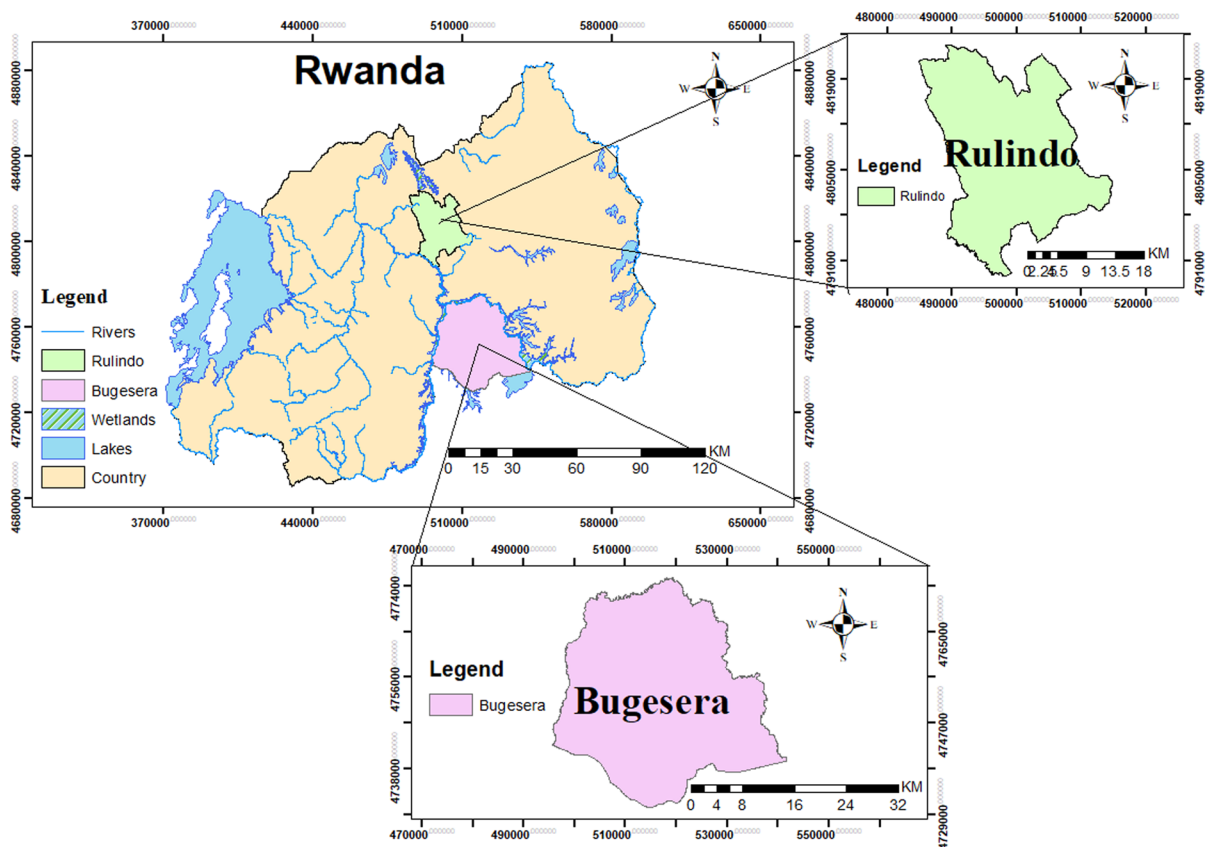


Fig. 1 Bugesera and Rulindo study areas from Rwanda map (adapted from CGIS)

Latitude 1°44'S and Longitude 29°59'E and is largely characterized by mountains (Ntawuruhunga et al. 2023a, b). It is rural and is comprised of steep hills and valleys, with springs, streams, and rivers serving as the traditional water sources in the region (Ndolimana and Nahayo 2021). It enjoys a tropical climate, characterized by alternating rainy and sunny seasons (Muhamadi and Boz 2021).

Sampling procedures and data collection

Data were collected from both primary and secondary sources. Primary data were obtained from the field made up of plant species and interviews with farmers on their farms. Secondary data were collected from published articles, scientific books, and policies on general conditions of the region, such as geographical aspects.

This study applied a multi-stage sampling procedure combining purposive, stratified, and simple random sampling techniques. In the 1st stage, the two regions described above were purposively selected based on their agroecological zones (Table 1) and the diversity of attributes of CSAF in terms of composition (species diversity), planting geometry, and configuration (spatial niches), and production. In the 2nd stage, the two geographical regions were stratified using their elevation: the lowland (Bugesera) zone and the highland (Rulindo) zone. In the 3rd stage, different villages were selected based on information gathered from extension officers about agricultural potential, accessibility, and high level of CSAF practices and production.

In determining the sample size (Table 2), this study used data published from the Rwanda Agricultural Household Survey Report 2020 (National Institute of Statistics of Rwanda, 2021). These data show that about 166,000 (45.60%) out of 364,000 (*N*) rural households in both the Bugesera and Rulindo are farmers. So, 381 (*n*) farmers were selected to form the total sample (Wonnacott and Wonnacott, 1969). Sampling intensity was proportionally allocated to each subsample based on farming population size. Finally, from the list of farmers selected for interview, a simple random sampling was used to select the sample units.

Lists of farmers from the selected villages were prepared with the assistance of village leaders and 381 farmers were randomly picked for interviews, of which, 193 farmers were from the Bugesera and 188 from the Rulindo. Interviews were organized with farmers on their farms.

The survey was conducted between April to September 2023 and gathered information on the extent of CSAF practices adoption and their utilities in the farming communities of Bugesera and Rulindo. Before surveying the selected regions, the questionnaires were pre-tested on 11 random farmers from the two separate study areas ((Bugesera (6 farmers) and Rulindo (5 farmers)) and later revised to fit into the context of the local biophysical, climatic, and socio-economic situations. The original questionnaire was built on an Open Data Kit (ODK) software uploaded on an Android mobile device (tablet) under the ODK collect Application. The built form on ODK included the Global Positioning System (GPS) capturing the

Table 1 Study area characteristics

Site name	Site code	AEZ	Latitude (°S)	Longitude (°E)	Altitude (m.a.s.l.)	Mean annual temperature (°C)	Mean annual rainfall (mm)
Bugesera	BU	Eastern lowlands	2°09'	30°05'	1,100–1,780	39	943
Rulindo	RU	Central Highlands	1°44'	29°59'	1,862–2,438	19	1,243.3

Table 2 Sampled sites and size

Sites	Households	Farmer households	Sample size (<i>n</i>)	% sample
Bugesera	204,000	84,000	193	50.66
Rulindo	160,000	82,000	188	49.34
Total	364,000	166,000	381	100.00

farm coordinates, socio-economic information, biophysical information, etc. Additional information was captured through field measurements using e.g., a GPS area calculation application uploaded on an Android mobile phone for land area measurement, observations on the ground, and interviews with key informants (including local/village leaders, agriculture extension officers, and farmer groups).

Definition of variables used in the study

The variables of interest investigated in this study are presented in Table 3.

The structure and composition of trees in CSAF systems

Within each farmer’s farm, trees were counted and farm sizes were estimated using an Android device’s land area calculator software. Identified CSAF tree species were grouped into species and presented in tables, charts, percentages, relative frequencies, relative density, and important value index (IVI).

The computation of the Important Value Index (IVI) helps to evaluate the dominance of tree species in each site. The IVI is obtained by summing up relative density (RD) with relative dominance (RD), and relative frequency (RF) in each species (Mueller-Dombois and Ellenberg 1974). The following formula was used to calculate the IVI as per Cox (1995):

$$\text{Density}(D) = \frac{\text{Total number of individuals}}{\text{Size of farm}} \tag{1}$$

$$\begin{aligned} \text{Relative density (RD)} \\ = \frac{\text{Number of individuals of species}}{\text{Number of individuals of all species}} \times 100 \end{aligned} \tag{2}$$

$$\text{Frequency (F)} = \frac{\text{Number of quadrats in which species occurred}}{\text{Total size of farms}} \tag{3}$$

$$\begin{aligned} \text{Relative frequency (RF)} \\ = \frac{\text{Number of occurrence of the species}}{\text{Number of occurrence of all the species}} \times 100 \end{aligned} \tag{4}$$

$$\text{Dominance (Dm)} = \frac{\text{Total basal area of the species}}{\text{Total size of plots}} \tag{5}$$

$$\begin{aligned} \text{Relative dominance (RDm)} \\ = \frac{\text{Total basal area of the species}}{\text{Total basal area of all species}} \times 100 \end{aligned} \tag{6}$$

$$\text{IVI of tree} = \text{RD} + \text{RF} + \text{RDm} \tag{7}$$

Diversity index (H')

The diversity of tree species on a farmland was measured using the Shannon–Weiner diversity index (H’).

$$(H') = - \sum_{i=1}^s p_i (\ln p_i) \tag{8}$$

where (H’) is the Shannon-Weiner diversity index, *s* is the richness of tree species *i*, *p_i* is the ratio of the number of individuals of a species (*n*) and the total

Table 3 Description of variables and their expected signs

Variable	Description	Expected sign
CSAF practices available	Discrete variable: number counts	+
CSAF tree species reported	Discrete variable: number counts	+
Tree species density (H') in CSAF	Continuous variable: index ratio	+
Tree species evenness (E) in CSAF	Continuous variable: index ratio	+
Tree species richness (D _{mg}) in CSAF	Continuous variable: index ratio	+
Tree species share (similarity-S)/ CSAF	Continuous variable: index ratio	+
Tree species dominance (D) in CSAF	Continuous variable: index ratio	+
Tree species importance (IVI) in CSAF	Continuous variable: index ratio	+
Best management practice (BMP)	Continuous variable: percentage	+
Utility derived from CSAF	Continuous variable: percentage	+

number of individual trees (N) or (n/N) Kiyani et al., 2017).

According to Michael (1995), a value of diversity index lower than 1.50 ($H' < 1.50$) means the diversity is low, while a value ranging between $1.50 < H' < 3.5$ means the diversity is moderate, higher than 3.5 ($H' > 3.5$) means the diversity is high.

Similarity index (S)

A similarity index (S) was computed to test how similar or dissimilar the two contrasting agroecological zones of Bugesera and Rulindo were in terms of CSAF trees. In this regard, Sørensen’s index (Mukoo-bwa et al. 2023) was computed as follows:

$$S = \frac{2a}{2a + b + C} \tag{9}$$

where S is the computed Sørensen similarity index, a is the number of species shared between CSAF system types of the assessed pair (Bugesera and Rulindo), b is the number of species present only in a certain agroecological zone, and c is the number of species present in another agroecological zone among the two zones being compared.

Margalef’s index (D_{mg})

The Margalef’s index (D_{mg}) was computed to measure the species richness as follows:

$$D_{mg} = \frac{(S - 1)}{\ln(N)} \tag{10}$$

where,

- D_{mg} =Index of richness.
- S =Total of species to be found.
- N =Total of individuals.

Margalef (1968) isolates three categories of species richness index, namely low ($D_{mg} < 2.5$), moderate ($2.5 < D_{mg} < 4.0$), and high ($D_{mg} > 4.0$).

Evenness index (E)

The evenness index (E) estimates the level of evenness of individuals per species. The index of evenness (E) is computed using the formula (Magurran 1988):

$$E = \left(\frac{H'}{\ln S} \right) \tag{11}$$

where,

- E =Index of evenness.
- H' =Index of Diversity.
- S =Total of species.

Odum (1996) classified species evenness indices in order of importance this way: evenly distributed ($E \geq 0.75$), moderately distributed ($0.5 \leq E \leq 0.75$), and unevenly distributed ($E \leq 0.5$).

Dominance index (C)

The species dominance index (C) is computed to show the dominance of a species in a farming community. C is computed using the formula developed by Misra (1980):

$$C = \sum_{i=1}^n \left(\frac{n_i}{N} \right)^2 \tag{12}$$

where,

- C = Dominance index.
- n_i = Density to— i .
- N = Total density.

The computed dominance index (C) values range from 0 to 1 ($0 \leq C \leq 1$). The dominance is high when the computed value is close to 1. Inversely, if the C value is close to 0, it means no species dominates the ecosystem.

Testing best management practices (BMP) in the CSAF systems

Investigating CSAF best practices in the study areas and other requirements intended to promote multiple productive, protective and management outcomes e.g., landscape restoration and multi-dimensional utilities. Data for computing the BMP implementation rate were collected for each agroecological zone (Bugesera and Rulindo). Site surveys were conducted on randomly selected sites that were recently harvested (in Rwanda typically, large harvests take place in June–July–August). The main farm crops were Irish potatoes, maize, cassava, and beans. These crops are among the priority crops (Kathiersan 2012) inventory set forth by the government of Rwanda in its program implemented in 2008 termed ‘farmland use

consolidation' with the overall goal to overcome the effects of land fragmentation by increasing the scale of agricultural yields and stimulating an agrarian transformation for a competitive and market-oriented agricultural sector.

To ascertain whether farmers adopted CSAF's best management practices, we sought answers to the questions of whether farmers follow certain farming approaches to choose suitable sites and species, and how they maintain and manage trees (on-farm planting practices) over time, e.g. planting according to climate conditions, tree root pruning, branching, mulching, weeding, thinning, etc.

Construction of a weighted utility index

Utilities were assessed within the Expected Utility Theory (EUT) framework and were categorized into: fruits; timber/pole; bioenergy (firewood, charcoal); fodder; stakes for climbing crops (beans, coffee); fence tools; ethnomedicine (ikirogora, umusave, umubirizi, umutagara, umunyinya, umuvumu, umuko, umuziwaziwa); landmarking; cultural values (umuko, umuvumu); soil protection and control; other environmental services (soil retention, soil fertility, shade, shelterbelt/windbreak, micro/macro climate regulation); and others (not categorized above or no answers provided). Following the above order of utilities, we assume that some of the respondents could mention more than two utilities for one tree species in order of importance, the primary utility being ranked as the most important and others being ranked as secondary. By applying the formula of Iiyama et al. (2018), we created a weighted utility index that captures and reflects the multi-dimensional utilities of specific tree species.

When recording data, the respondents were allowed to provide a zero—minimum to a six—maximum secondary utilities per tree species for the CSAF adoption category. On that account, a score of 0.7 was arbitrarily assigned for the primary utility and a score of 0.3 to be divided among the secondary utilities as 0.3 is divisible by any number from 1 to 6 (Iiyama et al. 2017). We then computed the utility scores for each tree species mentioned by a respondent (in priority order) using the formulae and rules detailed in Box 1 (ibid.). As an illustration, if a respondent mentioned the fuelwood to be the only utility derived from *Eucalyptus urophila* on his/her farm, this species was assigned a score of 1.0 for fuelwood. Concurrently, if a respondent declared that *Eucalyptus urophila* is primarily for fuelwood, but also for soil protection as a secondary benefit, then the species was given 0.7 as the fuelwood score and 0.3 as the soil protection score. Moreover, if more than two secondary utilities are cited by the respondent, aside from fuelwood as the primary utility, say soil protection and bean/coffee stakes, then the species got the scores as fuelwood = 0.7, soil protection = 0.15, stakes = 0.15.

As a rule of thumb, the score for one particular species would not exceed 1.0, but with higher numbers of secondary utilities, the scores would be subdivided among the multiple utilities. Once utility scores were computed for each species, they were aggregated by utility types for each respondent and were also used as weights to disaggregate all the tree stands managed by a farmer by distinctive utilities.

Given the absence of commonly used quantitative measures to assess the scaling up of CSAF (for example: percentage of land area or population

Box 1 Formulae and rules for computing and assessing weight utility scores from ranks. *Source* Adapted from Iiyama et al. (2017)

$U_{ALL} = 1.0 \times U_{primary}$ (fuel, charcoal, fodder...), if counts of $U_{others} = 0$

$U_{ALL} = 0.7 \times U_{primary}$ (fuel, charcoal, fodder ...) and 0.30 for $U_{others} 1 \dots 6$ (fuel, ...), if counts of $U_{others} = 1$

$U_{ALL} = 0.7 \times U_{primary}$ (fuel, charcoal, fodder ...) and 0.15 for $U_{others} 1 \dots 6$ (fuel, ...), if counts of $U_{others} = 2$

$U_{ALL} = 0.7 \times U_{primary}$ (fuel, charcoal, fodder ...) and 0.10 for $U_{others} 1 \dots 6$ (fuel, ...), if counts of $U_{others} = 3$

$U_{ALL} = 0.7 \times U_{primary}$ (fuel, charcoal, fodder ...) and 0.075 for $U_{others} 1 \dots 6$ (fuel, ...), if counts of $U_{others} = 4$

$U_{ALL} = 0.7 \times U_{primary}$ (fuel, charcoal, fodder ...) and 0.06 for $U_{others} 1 \dots 6$ (fuel, ...), if counts of $U_{others} = 5$

$U_{ALL} = 0.7 \times U_{primary}$ (fuel, charcoal, fodder ...) and 0.05 for $U_{others} 1 \dots 6$ (fuel, ...), if counts of $U_{others} = 6$

where U_{ALL} , which denotes the utility portfolio of one particular tree species, consists of $U_{primary}$ and U_{others} which mean the primary utility and secondary utilities respectively

engaged in CSAF implementation), the adoption at scale was defined loosely if a CSAF is considered a common practice in an area by many land managers or communities (Willemen et al. 2013).

Data and statistical analysis

The ArcGIS 10.8 software from Esri (Redlands, California, USA) was used for map extraction and location of Bugesera and Rulindo study areas where data were collected. In addition, both descriptive statistics (to compute mean and standard deviation statistics) and inferential statistics (ANOVA test for independent groups and probability values) were utilized to analyze the data. This step aimed to compare the adoption and non-adoption of CSAF among farmers in a cross-site comparative analysis. Thus, the ANOVA for parametric data was used and when data could not be transformed to meet the assumptions of normality, the Kruskal–Wallis test was performed. Species and survey data were summarized using Excel and R software (R Development Core Team, 2014).

Results

CSAF practices available in the study areas

Table 4 shows that farmers in study areas practice CSAF on farms with different technologies for various purposes—taungya, home gardens, alley cropping, improved fallow, multipurpose trees, plantation crop combination, shelterbelts/windbreaks, and silvopasture. Results showed that 18.9% of farmers practiced home garden CSAF technologies in Bugesera whereas in Rulindo the same proportion practiced shelterbelts/windbreaks CSAF technologies on farms. In contrast, in Bugesera, alley cropping was the CSAF technology used by a small proportion of farmers (0.52%) whereas in Rulindo the same proportion practiced silvopasture CSAF technologies on farms.

Taungya was not recorded in any area of our case study. Taungya practice also called agro-silviculture involves growing, along with forest tree species, annual crops during the early year stages of the establishment of forest trees (Ndomba et al. 2015). Taungya originated in Southeast Asia (Burma, now Myanmar and Thailand) where it was introduced

to restore tree cover following shifting cultivation. Taungya is a Burmese word meaning “cultivation on the hills” (Vieira et al. 2009). The interval is three to five years depending on tree species, initial tree spacing, and the species growth rate (Ndomba et al. 2015). Within three to five years, crop species are not expected to compete with tree growth and there are complementary effects between these two species (crops and trees). By the end of the last year (third or fifth) of Taungya, the tree canopy is deemed to cast much shade for normal growth of the seasonal crops, thus the cultivation of crops is stopped (Lambrecht et al. 2002). Taungya is believed to be one of the cheapest means of establishing tree covers on the one hand and improving food security and the community’s livelihoods, on the other hand (Akinbisoye et al. 2014).

Following the lack of records on *Alnus* spp. and *Calliandra calothyrsus* tree species in Bugesera, Fig. 2 isolates a few (four) typical CSAF tree species that featured the major CSAF landscapes defined by configuration in each of the farming systems. In Bugesera, major CSAF practices were homestead-planted trees of *Citrus sinensis* (14.83%) and *Grevillea robusta* (14.35%), and improved fallow (7.18%) and multipurpose trees (7.18%), respectively. In addition, *Grevillea robusta* was more likely found boundary-planted in Bugesera (6.70%) as shelterbelts/windbreaks. In the Rulindo area, *Grevillea robusta*, *Citrus sinensis*, and *Persea americana* were boundary-planted (shelterbelts/windbreaks) symbolic tree species (13.60%), (9.90%) and (8.83%), respectively. Additionally, the same tree species were homestead (8.46%), (10.29%), (5.88%), and alley cropping (7.35%), (6.62%), (4.04%) planted. In Rulindo, CSAF trees are mostly boundary-planted compared to Bugesera to serve the role of soil protection against erosion on steep hillslopes.

Tree species composition in the study areas

In total, 6,554 individual CSAF trees belonging to 6 species in 6 families were identified in this study (Table 5). The total number of CSAF tree species recorded was 3,425 in Bugesera and 3,129 in Rulindo. Of the species of trees identified, 4 of them, namely *Citrus sinensis*, *Eucalyptus urophylla*, *Grevillea robusta*, and *Persea americana* were found in both agroecological zones (AEZs). All the recorded trees

Fig. 2 Key CSAF tree species by configuration in each study area

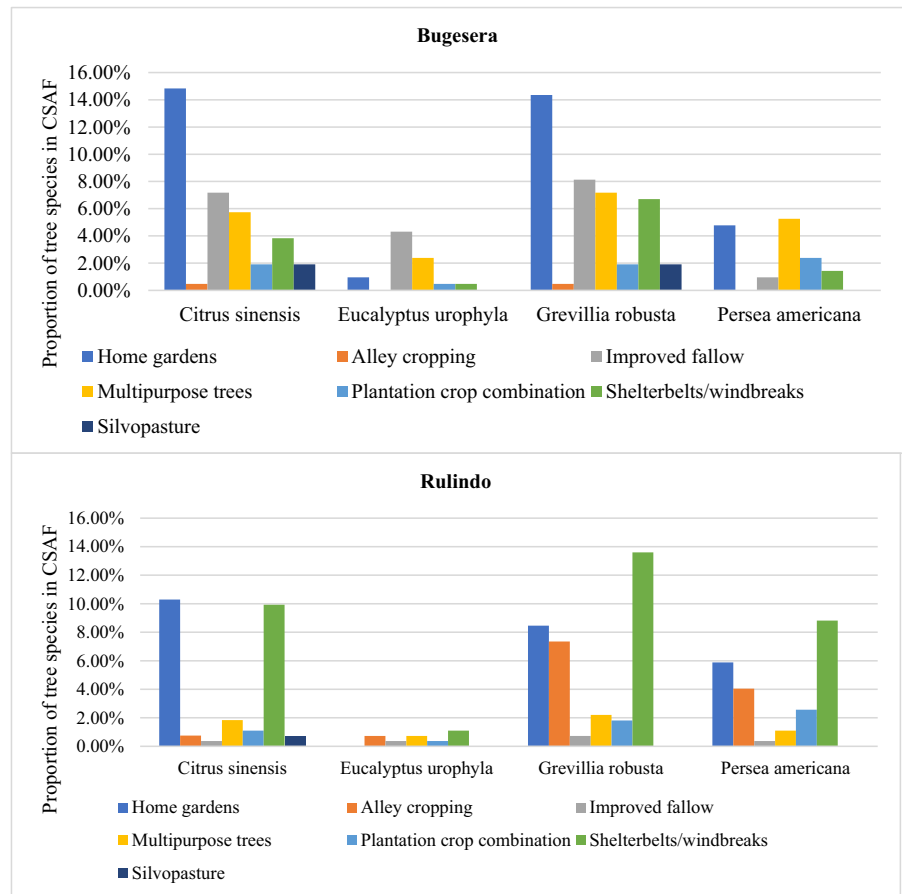


Table 4 CSAF practices in study areas

	Bugesera ($n = 193$)	Rulindo ($n = 188$)	Total ($n = 381$)	Mean (\pm SD)
	Freq. (n)	Freq. (n)	Freq. (n)	
Taungya	–	–	–	–
Home gardens	72	49	121	60.50(\pm 16.26)
Alley cropping	2	36	38	19.00(\pm 24.04)
Improved fallow	43	5	48	24.00(\pm 26.87)
Multipurpose trees	34	13	47	23.50(\pm 14.85)
Plantation crop combination	11	11	22	11.00(\pm 0.00)
Shelterbelts/windbreaks	23	72	95	47.50(\pm 34.65)
Silvopasture	8	2	10	5.00(\pm 4.24)
Total	193	188	381	190.50(\pm 3.53)

were exotic tree species. However, this does not preclude that to some extent, rare indigenous species are observed on marginal, abandoned, and barren soils in the two settings. More than half (52.26%) of individual CSAF trees were found in Bugesera whereas

slightly less than half (47.74%) were recorded in Rulindo. The largest number of individual CSAF tree species recorded were (41.13%) in both settings whereas the smallest recorded individual trees were *Calliandra calothyrsus* (1.14%). The largest number

Table 5 Tree species

SN	Species	Family	Bugesera Counts	Rulindo Counts	Total Counts	Mean (\pm SD)	<i>p</i> value
1	<i>Alnus</i> spp.	<i>Betulaceae</i>	0	85	85	0.22(\pm 2.08)	0.001*
2	<i>Calliandra calothyrsus</i>	<i>Fabaceae</i>	0	75	75	0.20(\pm 1.52)	0.000*
3	<i>Citrus sinensis</i>	<i>Rutaceae</i>	300	541	841	2.21(\pm 18.01)	0.415
4	<i>Eucalyptus urophylla</i>	<i>Myrtaceae</i>	1,395	1,301	2,696	7.07(\pm 77.69)	0.402
5	<i>Grevillea robusta</i>	<i>Proteaceae</i>	582	916	1,498	3.93(\pm 9.67)	0.000*
6	<i>Persea americana</i>	<i>Lauraceae</i>	1,148	211	1,359	3.57(\pm 51.46)	0.000*
	Total		3,425	3,129	6,554	3,277(\pm 209.3)	0.423

*significant at 0.05

Table 6 The diversity of CSAF tree species in Bugesera and Rulindo

	Sites		Average
	Bugesera	Rulindo	
Taxa_sums	4	6	
Individuals	3,425	3,129	
Shannon_H'	1.24	1.40	1.40
Evenness_E	0.90	0.78	0.78
Margalef_Dmg	0.37	0.62	0.57
Dominance_D	0.12	0.19	0.09

of individual *Persea americana* (household source of income and food security) trees (17.51%) are grown in Bugesera compared to Rulindo (3.22%). Conversely, *Citrus sinensis* is more grown in Rulindo (8.25%) than in Bugesera (4.58%). *Alnus* spp. (1.29%) and *Calliandra calothyrsus* (1.14%) were documented solely in Rulindo with no record in sampled farms of Bugesera. There was a significant mean difference in CSAF tree species found in both AEZs for *Alnus* spp. ($p < 0.001$), *Calliandra calothyrsus* ($p < 0.001$), *Grevillea robusta* ($p < 0.001$) and *Persea americana* ($p < 0.001$). Mean differences in CSAF tree species found in both settings were not statistically significant for *Citrus sinensis* ($p = 0.4158$) and *Eucalyptus urophylla* ($p = 0.4028$).

The tree species diversity in CSAF

Six CSAF tree species were identified across the two AEZs except for *Alnus* spp. and *Calliandra calothyrsus* missing in Bugesera (Table 6). The diversity of the six CSAF tree species identified in the

two separate settings is shown in Table 6. Using the Shannon index formula, it was observed that Rulindo has the highest values for tree species' diversity ($H' = 1.40$) compared to Bugesera ($H' = 1.24$). Since the Shannon indices in both settings are lower than 1.50 ($H' < 1.50$), it implies that the diversity of tree species is low in these two contrasting AEZs.

The tree species evenness in CSAF

Regarding the CSAF tree species' evenness (Table 6), Bugesera had the highest values for tree species' evenness ($E = 0.90$) compared to Rulindo ($E = 0.78$). Since the evenness values in both sites are higher than 0.7 ($E \geq 0.75$), it implies that tree species are evenly distributed.

The tree species richness in CSAF

Computed CSAF tree species richness (Table 6) showed the highest values in Rulindo ($D_{mg} = 0.62$) compared to Bugesera ($D_{mg} = 0.37$). Since the values for tree species richness in both sites are lower than 2.5 ($D_{mg} < 2.5$), it suggests a low tree species richness in these landscapes.

The tree species dominance in CSAF

Lastly, Sørensen's similarity index (Table 6) showed high similarity ($S = 0.80$) for trees between the two landscapes. Further, both Bugesera ($D = 0.12$) and Rulindo ($D = 0.19$) had a low dominance index suggesting a more even distribution of species, and no tree species dominates the sampled farms.

Table 7 Tree species important value index in the study area

Species	Bugesera			Rulindo		
	RF	RD	IVI	RF	RD	IVI
<i>Alnus spp</i>	0.00	0.00	0.00	4.93	2.71	7.64
<i>Calliandra calothyrsus</i>	0.00	0.00	0.00	39.91	2.39	42.30
<i>Citrus sinensis</i>	22.22	8.76	30.98	4.48	17.29	21.77
<i>Eucalyptus urophylla</i>	12.82	40.73	53.55	7.62	41.58	49.20
<i>Grevillea robusta</i>	41.02	17.00	58.02	29.15	29.27	58.42
<i>Persea americana</i>	23.93	33.52	57.45	13.90	6.74	20.64

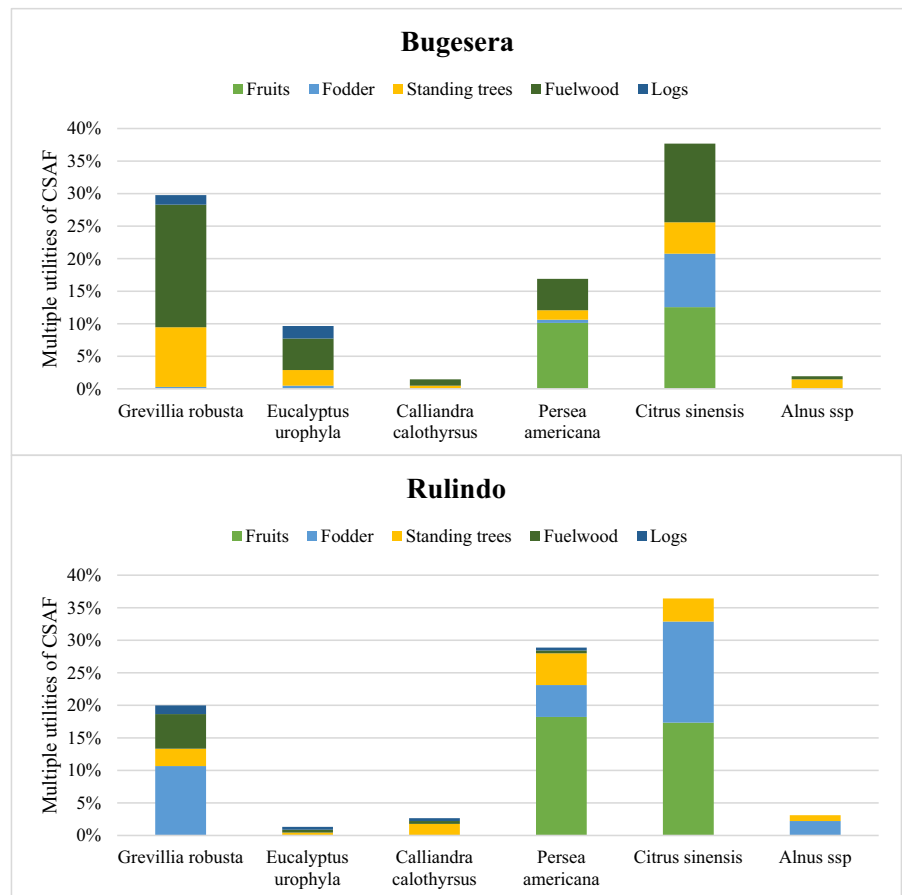
RF relative frequency, RD relative density, IVI important value index

Grevillea robusta was the most important tree species in Bugesera and Rulindo with IVI values of (58.02) and (58.42), respectively. Likewise, *Eucalyptus urophylla* was the most abundant tree species in both separate sites with an RD value of (40.73) in Bugesera and (41.58) in Rulindo (Table 7).

CSAF best management practices (BMP)

The analysis of CSAF's best management practices sought to ascertain whether farmers follow certain farming approaches to choose suitable sites and species, and how they maintain and manage trees (on-farm planting practices) over time (Table 8). On average, the results showed that CSAF best management

Fig. 3 Multiple utilities derived from key tree species observed in the CSAF of each study site



practices were found to be low in both the AEZs. Farmers practiced these skills below average except the branch pruning practiced at 60.11% in the Rulindo agroecosystem.

Utilities

Figure 3 shows that the major CSAF tree species dominant for the respective AEZs were perceived by farmers to serve multiple goals. There were variations in utility preferences from specific tree species across the two contrasting AEZs. For instance, *Citrus sinensis*, which was adopted by over 18% of surveyed farms in Bugesera and Rulindo (Fig. 3), was associated with utilities such as fuelwood and the sale of standing trees. The provision of fuelwood was given a higher weight in Bugesera (18.84%) than in Rulindo (5.33%). Furthermore, farmers gave higher weight to fuelwood for *Grevillea robusta* in Bugesera (18.84%) while in Rulindo farmers gave a higher weight to fruits for *Persea americana* (18.22%). *Persea americana* and *Citrus sinensis* which were primarily introduced to fight malnutrition, were perceived also to provide fuelwood in Bugesera and trees for climbing crops (stakes for beans and coffee) in Rulindo which gave varying weights to different utilities.

Figure 4 presents the proportions of farmers adopting different CSAFs by utility. Over 38.57% of surveyed farmers across the two AEZs referred to fruits as the major utility derived from tree species in their farms. Specifically, higher proportions of farmers referring to fruits were found in Rulindo located in the temperate zone of the central highlands of Rwanda (Fig. 4). Inversely, farmers in Bugesera,

which is located in the eastern dry savannah lowland of Rwanda, reported fuelwood as an important utility compared to those in Rulindo. The adoption of tree species for the utility of fodder varied considerably across the two regions, relatively low in Bugesera and more adopted in Rulindo where land fragmentation is high and zero grazing is commonly practiced. In general, farmers seemed to give more weight to utilities from goods meant for household survival such as fruits (home consumption), fuelwood (home cooking), fodder (cattle-housed for zero-grazing), and standing trees (stakes for climbing beans and coffee). Logs meant for commercial purposes were given the least weight.

Similarly, farmers referred to income generation (19.23%) and food security (16.86%) as the major utility derived from tree species in their farms. Nonetheless, some farmers still regarded ecosystem services as important secondary or subsidiary utilities derived from CSAF (Fig. 5).

Discussion

Diversified CSAF practices in farming systems

This study identified seven major climate-smart agroforestry (CSAF) technologies in Bugesera and Rulindo regions to wit: home gardens, alley cropping, improved fallow, multipurpose trees, plantation crop combination, shelterbelts/windbreaks, and silvopasture. Farmers predominantly utilized exotic trees such as *Alnus* ssp., *Calliandra calothyrsus*, *Citrus sinensis*, *Eucalyptus urophylla*, *Grevillea robusta*, and

Fig. 4 Adoption of CSAF defined by utilities (fruits, fodder, standing trees, fuelwood, logs)

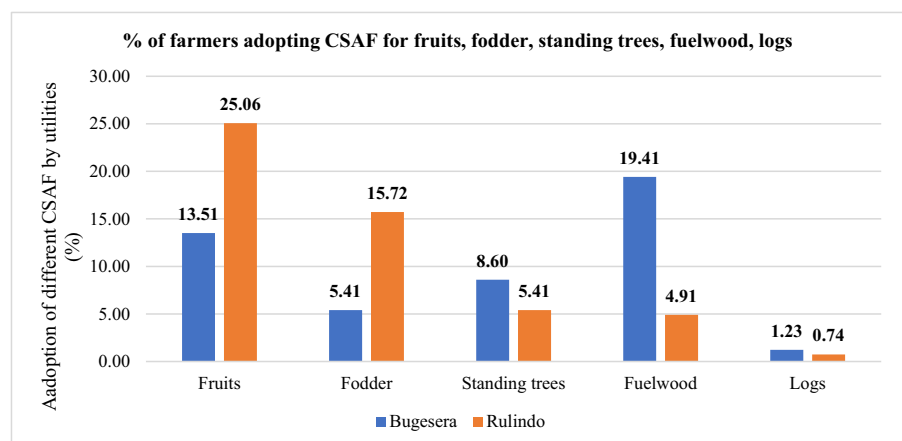


Fig. 5 Adoption of CSAF defined by utilities (soil control, soil fertility, agro-ecological, economic, food security)

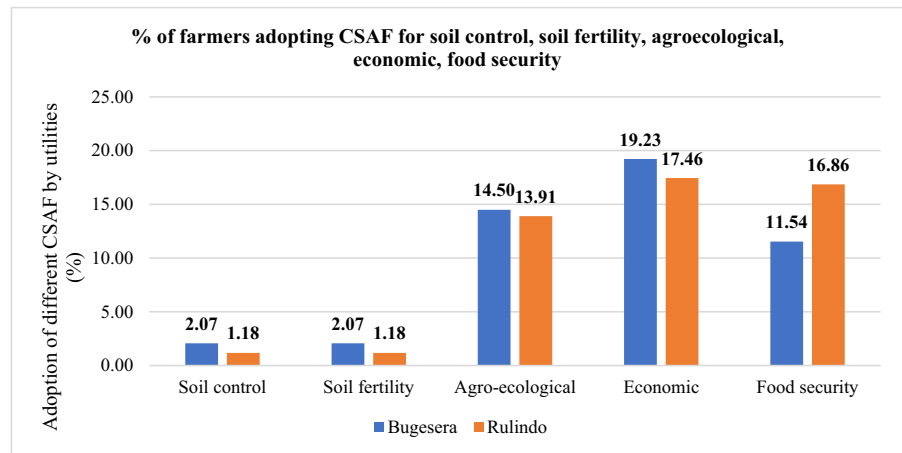


Table 8 BMP analysis

BMP	Bugesera (n = 193)		Rulindo (n = 188)	
	Yes	No	Yes	No
On-farm planting practices				
Preferred climate-smart agroforestry system/practice	22.28%	77.72%	25.53%	74.47%
Site conditions (e.g. slope, soil type)	22.80%	77.20%	27.66%	72.34%
Region and environmental conditions of your farm	24.87%	75.13%	27.13%	72.87%
Provide the trees with compost/manure	12.95%	87.05%	23.40%	76.60%
Use dry residues as mulch	8.81%	91.19%	12.23%	87.77%
Protect the growing tree from too much sun	5.18%	94.82%	12.23%	87.77%
Irrigate the young tree daily when rain is absent	2.59%	97.41%	11.70%	88.30%
Weed the plant regularly and prune when necessary	7.25%	92.75%	14.89%	85.11%
Use ash to protect the tree from ants and termites	0.00%	100.00%	5.32%	94.68%
Maintaining on-farm tree growth over time				
Replanting	6.74%	93.26%	6.91%	93.09%
Root pruning	22.80%	77.20%	25.00%	75.00%
Branch pruning	43.52%	56.48%	60.11%	39.89%
Thinning	15.03%	84.97%	22.34%	77.66%

Persea americana (avocado). While native trees like *Markhamia lutea* (Umusave), *Ficus* spp. (Umuvumu), *Vernonia amygdalina*, *Iboza riparia*, Umurehe, Umuko, Umutagara, Umubirizi, Umunyinya (*Acacia sieberiana*), umuvumu, and *Erythrina abyssinica* were present, their prevalence was lower compared to exotic species. They are observed mostly on marginal, abandoned, and barren soils. This aligns with Ndayambaje et al. (2014), emphasizing the historical introduction and preference for exotic over indigenous tree species in Rwanda. Elsewhere, bamboo (*Bambusa vulgaris*) and *Alnus ssp* were primarily planted along

waterway banks in Rulindo to prevent soil deposition during heavy rains, especially given its abundance of springs, streams, rivers, torrents, and valleys.

Despite the presence of CSAF tree species in these AEZs, in some parts of Rulindo overlooking Kigali City, there is a large exploitation of mines and quarries (e.g., Rutongo mining) which leads to environmental degradation. The majority of residents in these sites derive their daily living from jobs in mines with less involvement in farming which they consider less rewarding. *Persea americana* is the dominant tree species in this area due to its proximity to the City of

Kigali for commercial purposes in city markets and fruit processing plants (e.g., jams, juices, jellies, muffins, cakes).

In contrast, Bugesera lowland in Eastern Rwanda is home to many lakes and marshlands. CSAF trees are mostly found alongside main roads and have been planted by the government to protect road infrastructures and the environment. Many parts are exposed to rocks due to forest clearing (some years back, Bugesera was a theatre of tree cutting for charcoal to supply Kigali City). In addition, the land is strongly threatened by soil erosion leading to high depletion of soil fertility (Mikwa et al., 2014). There are many village settlements without trees around homesteads to prevent extreme heat, wind erosion, solar radiation, and violent wind during storms which render families homeless by blowing off rooftops of residential houses. Located in the savannah of the eastern lowland, Bugesera is suitable for modern farming with irrigation technologies (not rain-fed agriculture) as this zone is adjacent to the Akanyaru and Akagera rivers with many water bodies (lakes and marshlands).

Predominant tree species composition in CSAF

This study identified six tree species to wit: *Alnus* ssp., *Calliandra calothyrsus*, *Citrus sinensis*, *Eucalyptus urophylla*, *Grevillea robusta*, and *Persea americana* (avocado). Four of these species, *Citrus sinensis*, *Eucalyptus urophylla*, *Grevillea robusta*, and *Persea americana*, were found in both Bugesera and Rulindo agroecological zones. Of note, it is crucial to acknowledge the site-specificity before considering upscaling efforts (Mbow et al. 2014), as CSAF's potential varies depending on local conditions, knowledge, attitudes (perceptions), traditions, and not all options are universally viable as farming is not a one-size-fits-all practice.

The study found that in Bugesera, major CSAF practices were homestead-planted trees of *Citrus sinensis* and *Grevillea robusta*, improved fallow, and multipurpose trees. They are homestead planted likely to protect houses against wind erosion and to provide shade and fresh air during the excessive heat in the 7-month dry season. These findings corroborate Jemal et al. (2018) who, during their study on the contribution of CSAF on food and nutritional security in southwestern Ethiopia, found that the highest

number of exotic tree species occurred in home gardens. Additionally, Hartoyo et al. (2020) found comparable results that the local community in Andongrejo Village, Jember Regency, East Java, Indonesia, planted crops combined with woody species in the yard of a house or land owned by a community close to a settlement. In Rwanda, considering the decrease of arable land consecutive to overpopulation, the government has set up a policy of zero grazing to bring more land into crop farming to cope with food insecurity and poverty in the country. Based on this decision, animal rearing is practiced in cowsheds and tree shades in homesteads except for farmers practicing large-scale livestock farming in ranches.

In Rulindo, *Grevillea robusta*, *Citrus sinensis*, and *Persea americana* were boundary-planted (shelterbelts/windbreaks) symbolic tree species. Inversely, in their study, Kebebew and Urgessa (2011) reported that fruit trees were the dominant group of tree species in the home gardens of Jimma zone, Oromia Region, Ethiopia. The disproportion in tree species dominance and structure suggests that species distribution is practice and system-specific (ibid.). Opposing results were reported by Jemal et al. (2018) who found that based on their origin, native tree species were more dense than exotic species on study sites which insinuated a high natural biodiversity endowment in their chosen study area.

Elsewhere, in Rulindo, CSAF trees are mostly boundary-planted compared to Bugesera to serve the role of soil protection against erosion on steep hillslopes and the supply of stakes for climbing crops (beans and coffee). These findings are in line with Bucagu et al. (2013) who found that in the highlands zone of Rwanda, climbing beans are widely grown for stakes high demand where they give more than twice the yield from local bush beans, and play a key role in food security.

Tree species structure and composition in CSAF

Using the Shannon index formula, it was spotted that Rulindo has the highest index values for tree species' diversity ($H' = 1.40$) compared to Bugesera ($H' = 1.24$). The high diversity index in Rulindo may be attributed to the favorable climate conditions in that area. Bugesera is a semi-arid zone and less agroecologically favored in terms of rainfall and soil fertility than Rulindo in the temperate highlands. A

multiple variety of tree species, mainly exotics, are likely to thrive in temperate highlands where soil is humid, and intensive planting and management are favorable. Inversely, in semi-arid conditions, moisture stress constrains the survival of planted tree seedlings and only drought-resistant native trees are likely to survive. This finding aligns with Muhamadi and Boz (2021) who reported that regular rainfalls in the tropical climate of Rulindo offer favorable farming activities. Additionally, Rulindo's hydrology, climate, and topography make this part of the country endowed with tree diversity system landscapes. Another reason for the difference in the diversity index may be attributed to the tree survival rate of seedlings' inappropriate handling methods while planting. Poor tree survival may also have resulted from poor control and follow-up by extension services. This situation has direct implications on the efforts in the fight against desertification, and other climate change effects.

Regarding the CSAF tree species' evenness, Bugesera had the highest values for tree species' evenness ($E=0.90$) compared to Rulindo ($E=0.78$). Bugesera is known to experience a seven-month drought and an annual mean temperature of 21 °C (Mikwa et al., 2014). Thus, this climate is deemed too dry for optimal plant growth and agriculture suitability for development (Verdoodt and van Ranst, 2003).

Computed CSAF tree species richness showed the highest values in Rulindo ($D_{mg}=0.62$) compared to Bugesera ($D_{mg}=0.37$). In addition, Sørensen's similarity index showed high similarity ($S=0.8$) for trees between the two AEZs. Further, both Bugesera ($D=0.12$) and Rulindo ($D=0.19$) had a low dominance index suggesting a more even distribution of species in the sampled farms. There was a significant mean difference in CSAF tree species found in both sites for *Alnus ssp*, *Calliandra colothyrus*, *Grevillea robusta*, and *Persea americana*. Mean differences in CSAF tree species found in both settings for the remaining species (*Citrus sinensis* and *Eucalyptus urophylla*) were not statistically significant.

Mukoobwa et al. (2023) confirmed our findings that on-farm tree species identified in the different AEZs of Rwanda are varied. In a study by Garcia-Barrios and Ong (2004), nine on-farm tree species were reported in the Busogo sector, a highland zone in northern Rwanda, and six in the Bugarama sector, a lowland zone in south-western Rwanda. Elsewhere,

NISR (2012) identified seven CSAF tree species across six AEZs of Rwanda. Furthermore, Garcia-Barrios and Ong (2004) reported a more on-farm tree species diversification in the Musebeya sector of the Nyamagabe district with 12 tree species and even a bigger tree number (14 species) was reported in the Mpanga sector of the Kirehe district in the eastern savannah lowlands of Rwanda (Uwera et al. 2022).

The variation in CSAF tree species composition recorded between the two separate AEZs could be attributed to site-specificity, the farmers' know-how, and biophysical, ecological, socio-economic, and cultural conditions. This finding agrees with Hartoyo et al. (2020) who reported that since land management is implemented on the lands occupied by the local community, the species found on the lands are planted based on the needs of that community. In either case, Mukoobwa et al. (2023) supported our findings in their study, stressing that such variation can be a result of combined attributes such as edaphic and climate-feature conditions, and increased farmers' awareness correlated with extension services, and availability of seedlings and cultivars that suit local conditions, among others. Another study by Hartoyo et al. (2018) reported that because the index value of diversity is largely affected by the index value of richness and evenness of the species resulting in diverse combinations, the index value of diversity itself is very complex to report and interpret. In this angle, the species richness index value can be increased by selecting the right cultivar type (tolerant or intolerant) and applying a proper and suitable planting, maintaining, and managing by considering soil property and utility requirements. It is apparent that in some parts of Bugesera (e.g. Rweru, Ruhuha, Ngeruka, and Rilima), farmers prefer maintaining indigenous species in place of planting new, exotic species since indigenous trees (e.g. umunyinya, umuvumu) resist drought and fungi (e.g. termites), and require no extra efforts for maintenance.

CSAF best management practices

On average, the results showed that CSAF best management practices were found to be low in both the AEZs. Farmers practiced these skills below average except the branch pruning practiced at 60.11%

in the Rulindo agroecosystem. Karnatz et al. (2023) observed that adherence to BMPs should lead to a balance between the conservation of imperiled species and forest product generation. Chavan et al. (2018) concurred that understanding tree management techniques may lead to improved adoption of CSAF in rural areas where poverty is notable, and land management and farming remain a major concern for policymakers and development partners.

CSAF practices-derived utilities

Results showed that the major CSAF tree species dominant for the respective AEZs were perceived by farmers to serve multiple goals. This finding is confirmed by Iiyama et al. (2018) who asserted that in Rwanda and elsewhere, farmers may plant and manage selected tree species in spatial and temporal combination with crops to fulfill multiple productive functions of tree species depending on their locational flexibility. There were variations in utility preferences from specific tree species across the two contrasting AEZs. Farmers gave higher weight to fuelwood for *Grevillea robusta* in Bugesera (18.84%) while in Rulindo farmers gave a higher weight to fruits for *Persea americana* (18.22%). *Persea americana* and *Citrus sinensis* which were primarily introduced to fight malnutrition, were perceived also to provide fuelwood in Bugesera and trees for climbing crops (stakes for beans and coffee) in Rulindo which gave varying weights to different utilities. These findings follow Jemal et al. (2018) who reported that local farmers confirmed that fuel was mainly a by-product of perennial tree pruning, weeding, thinning, and clearing. Elsewhere, in-home garden-specific species, some CSAF tree species are cultivated solely for the production of fuel (ibid.). These results are similar to those by Iiyama et al. (2018) who emphasized that in highland zones, multi-purpose *Alnus* spp. contour hedgerow provide fuel, and stakes for commercial crops (passion fruits, tomatoes, eggplants, and coffee) as well as for soil erosion control.

In general, farmers seemed to give more weight to utilities from goods meant for household survival such as fruits (home consumption), fuelwood (home cooking), fodder (cattle-housed for zero-grazing), and standing trees (stakes for beans and coffee). Logs meant for commercial purposes were given the least weight. To some extent, the situation is similar to

Jemal and Callo-Concha (2017) concerning fodder, where they found that multipurpose trees supplement the hay obtained from the communal grazing lands.

Congruently, farmers referred to income generation and food security as the major utility derived from CSAF. The findings follow Jemal et al. (2018) who asserted that the diversity of CSAF practices plays an important role by providing fruits and fuel which ultimately increases the access of households to diverse and healthy foods. Nonetheless, some farmers still regarded ecosystem services as important secondary or subsidiary utilities derived from CSAF. Iiyama et al. (2018) reported that more households in highland systems reported bean stakes, timber/poles, soil erosion control, and other environmental services as important utilities derived from CSAF practices.

Conclusion

This study had fourfold objectives: (i) to analyze the distribution and composition of trees in CSAF systems, (ii) assess tree diversity in CSAF systems, (iii) analyze CSAF best management practices, and (iv) evaluate CSAF-derived utilities through a cross-site comparative study.

The study found that, in Bugesera, major CSAF practices were homestead-planted trees of *Citrus sinensis* and *Grevillea robusta*, improved fallow, and multipurpose trees. They are homestead planted likely to protect houses against wind erosion and to provide shade and fresh air during the excessive heat in the dry season. In Rulindo, *Grevillea robusta*, *Citrus sinensis*, and *Persea americana* were boundary-planted (shelterbelts/windbreaks) symbolic tree species. Specifically, in Rulindo, CSAF trees are mostly boundary-planted compared to Bugesera to serve the role of soil protection against erosion on steep hillslopes and the supply of stakes for climbing crops (beans and coffee).

It was found that Rulindo has the highest index values for tree species' diversity ($H' = 1.40$) compared to Bugesera ($H' = 1.24$). The high diversity index in Rulindo may be attributed to the favorable climate conditions in that area. On average, the results showed that CSAF best management practices were low in both the AEZs. Farmers practiced these skills below average except the branch pruning practiced at 60.11% in the Rulindo agroecosystem.

CSAF tree species dominant for the respective study areas were perceived by farmers to serve multiple goals, providing varied products such as timber, fuelwood, food and fodder, and stakes for climbing crops (beans and coffee) and income. *Persea americana* and *Citrus sinensis* which were primarily introduced to fight malnutrition, were perceived also to provide fuelwood in Bugesera and trees for climbing crops (stakes for beans and coffee) in Rulindo which gave varying weights to different utilities. In general, farmers seemed to give more weight to utilities from goods meant for household survival such as fruits (home consumption), fuelwood (home cooking), fodder (cattle-housed for zero-grazing), and standing trees (stakes for climbing beans and coffee). Logs and poles/timber meant for commercial purposes were given the least weight. It was clear in the study that there was a discrepancy in CSAF adoption between Bugesera (eastern savannah dry lowland) and Rulindo (central temperate highland).

An implication of these results is that various stakeholders would encourage farmers in research areas to upscale the practices of CSAF to increase farm productivity and derived tree products for income generation and food security. Sylvopasture which is overlooked in many parts of Bugesera should be promoted to protect pastures against extreme heat on livestock during the yearly 7-month long drought season. As shown, Bugesera (located in the savannah of the eastern dry lowlands) is endowed with untapped natural land resources, water bodies (numerous lakes), and swamps (Akanyaru and Akagera rivers), whose exploitations should be explored in depth, such as modern farming based on irrigation technologies and agricultural mechanization. Ultimately, we recommend that efforts be made to reinforce extension services to improve farmers' awareness of the role of CSAF on farm returns. Considering its effectuality, it cannot be gainsaid that ways of making seedlings available for planting should also be explored. This study will pave the way for further studies on the extent of CSAF tree covers in study areas and possibly planning developmental programs based on gaps singled out in this study.

Acknowledgements The authors acknowledge the financial support from the Partnership for Skills in Applied Sciences, Engineering, and Technology-Regional Scholarship and Innovation Fund (PASET-RSIF) which enabled them to carry out this study as part of doctoral studies at Sokoine University of

Agriculture (SUA). We acknowledge the assistance provided by staff at SUA, and Southern Africa Centre of Excellence for Infectious Diseases, SACIDS Foundation for One Health, SUA, Morogoro, Tanzania. A vote of thanks to local leaders in Bugesera and Rulindo who permitted this study to be carried out in their jurisdictions, district agronomists, extension workers, and farmers who spared their precious time to participate in this study.

Author contribution D.N.: Conceptualization, Methodology, Investigation, Formal analysis, Writing—original draft preparation, Software, Writing—review and editing, Visualization. E.E.N.: Writing—original draft, Methodology, Data curation, Validation, Writing—review and editing, Visualization, Supervision. H.O.M.: Writing—original draft, Methodology, Data curation, Validation, Writing—review and editing, Visualization, Supervision. R.J.S.: Writing—original draft, Writing—review and editing, Project administration, Supervision. K.L.L.: Writing—review and editing, Validation, Supervision. All authors have read and agreed to the published version of the manuscript.

Funding The authors did not receive support from any organization for the submitted work.

Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

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