Trees, Forests and People 16 (2024) 100552

Contents lists available at ScienceDirect

Trees, Forests and People

journal homepage: www.sciencedirect.com/journal/trees-forests-and-people

Assessment of stocking, productivity, and aboveground biomass of tree species used as fuelwood in Rwanda's agricultural landscapes☆

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ARTICLE INFO

Keywords:
Agroforestry
Fuelwood
Cooking
Stem density
Biomass

ABSTRACT

Tree-based systems (TBS) in the agricultural landscape of Rwanda do supply considerable amounts of fuelwood to the local communities. However, there needs to be more information on the available stocking, aboveground biomass (AGB), and productivity of the trees used for fuelwood. The study aims to assess the common tree species used for fuelwood and quantify the biomass stock across various TBS in the agricultural landscape. The study used a systematic sampling design, establishing 130 band transects, each measuring 2 km x 5 m. The transects were systematically distributed across the Bugesera and Musanze Districts, representing low and high-altitude regions. In Bugesera District, the common tree species for fuelwood use were *Grevillea robusta, Eucalyptus* spp., *Senna spectabilis,* and *Markhamia lutea*. The results indicated that the mean stem density and AGB of *Eucalyptus* spp. and *S.spectabilis* were substantially higher than other species. Across all TBS categories, trees covered an average stem density of 50 stems/ha and an AGB of 2.07t/ha. The stem density and AGB were substantially higher in boundary plantings and mixed cropping than in other TBS. Most trees in all TBS categories had a DBH ranging from 1 to 5 cm, except for the woodlot, where trees had a DBH ranging between 5.1–10 cm. In Musanze District, the common tree species for fuelwood use were *G.robusta, Eucalyptus* spp., *Alnus acuminata*, and *M.lutea*. The mean stem density, standing AGB, and productivity of *Eucalyptus* spp. were substantially higher than those of the other species. Across all TBS, trees covered an average stem density of 109 stems/ha and AGB of 5.38t/ha. The number of stems and AGB were substantially higher in boundary plantings and woodlots than in mixed cropping, live fences, and home gardens. Furthermore, the results on fuelwood supply indicated that *S.spectabilis* in Bugesera and *Eucalyptus* spp. in Musanze have a higher potential to produce higher biomass in short rotation.

1. Introduction

Tree-based systems (hereafter TBS) refer to trees integrated into agricultural landscapes. These include various agroforestry systems as well as woodlots dominated by exotic species (Iiyama et al., 2018). In most African countries, the adoption of different types and forms of TBS are influenced by several factors, including agro-climatic conditions, environmental challenges, land availability, and socioeconomic activities. For example, the Chagga home garden system, widely practiced in high-rainfall regions of northern Tanzania, uses a multi-layer agroforestry approach to address land scarcity effectively (Misana et al., 2003). This system's vertical layering of various crops and trees optimizes land utilization, promotes biodiversity, and enhances soil fertility (Misana et al., 2003). Similarly, in Rwanda, Uganda, and Burundi, TBS such as woodlots, live fences, home gardens, boundaries, and mixed cropping have been widely adopted to address challenges related to the scarcity of fuelwood, soil erosion, limited land and soil fertility (Iiyama et al., 2018; Kyarikunda et al., 2017; Nkurunziza et al., 2016; Rode et al., 2023; Kimaro et al., 2019). Tree-based systems are estimated to produce 20% of fuelwood in Africa and 70% in Asia (Sharma et al., 2016).

☆ This article is part of a special issue entitled: "Forest Science navigating sustainable development … A third task" published at the journal Trees, Forests and People.

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https://doi.org/10.1016/j.tfp.2024.100552

Available online 30 March 2024

Globally, over 2 billion people rely on fuelwood for cooking and heating (Amuzu-Sefordzi et al., 2016; Johnson and Bryden, 2012; Paulsen et al., 2019). In sub-Saharan Africa, about 81% of the population depends on woody biomass for household cooking energy and as a source of income through the sale of charcoal and firewood (Ajieh et al., 2023; Bildirici and Özaksoy, 2016). Cooking by biomass is used by about 96.6% of the population in Burundi (Sinzinkayo et al., 2015), 95% in Uganda, 90% in Tanzania (Felix and Gheewala, 2011), 85% in Rwanda (Hakizimana et al., 2020) and 68% in Kenya (Takase et al., 2021). Current fuelwood extractions from natural forests and plantation forests exceed the demand in most sub-Saharan African countries (Chidumayo, 2019b; Mainimo et al., 2022; Manyanda et al., 2020; Mudaheranwa et al., 2019; Ndayambaje and Mohren, 2011). Therefore, integrating on-farm multipurpose tree species has been suggested to be one of the most effective ways to increase the availability of fuelwood and other environmental services (Ndayambaje and Mohren, 2011; Scheid et al., 2018; Vyamana et al., 2021, 2023).

Adopting on-farm fuelwood production is crucial for ensuring a sustainable fuelwood supply and other significant wood products. It also serves as a strategic approach to alleviating pressure on the remaining natural forests and woodlands. The TBS in the agricultural landscape of Rwanda has the potential to supply fuelwoods to the local communities (Mainimo et al., 2022; Ndayambaje et al., 2014; Singh et al., 2021). Regrettably, there is a lack of information about on-farm fuelwood production, the available stem density, aboveground biomass (AGB), and productivity of the trees used for fuelwood, which hinders the ability to effectively advocate for the promotion the trees in the agricultural landscape (Dam te and Koch, 2011; Jerneck and Olsson, 2013; Kuyah et al., 2012). Enhancing fuelwood and wood production on-farm can be achieved by integrating TBS in the agricultural landscape, mainly focusing on the most preferred species for fuelwood production and fast-coppicing tree species. This study assesses the common tree species used for fuelwood within agricultural landscapes and quantifies the biomass stock across various TBS. Specifically, the study aimed to 1) Assess the stocking and distribution of the most common tree species used for fuelwood across various systems, including home gardens, mixed cropping, boundaries, live fences, and woodlots in Bugesera and Musanze Districts, 2) Quantify the aboveground biomass, and 3) Estimate the productivity of these common tree species for fuelwood use across different trees-based systems in Musanze and Bugesera Districts. The objective of this study was to put forth a hypothesis suggesting that there are notable variations in biomass stock and fuelwood productivity within different tree-based systems (TBS) and among tree species within these systems in the agricultural landscapes of Bugesera and Musanze Districts. In addition, it suggests that species selected for short rotation cycles exhibit distinct variations in growth and biomass accumulation, contributing to fuelwood supply. The hypothesis underscores the influence of management practices, species selection, and specific TBS characteristics on fuelwood production, highlighting the assumption that both the choice of species and the design of the TBS, including spatial organization, management intensity, and species composition play crucial roles in optimizing fuelwood productivity while also fostering biodiversity conservation.

2. Materials and methods

2.1. Study areas

The tree species were inventoried in all sectors of the two study districts (Fig. 1), Bugesera and Musanze Districts, representing low and high-altitude regions and different agroclimatic conditions of Rwanda. Bugesera is located in the lowland regions at 1000–1500 m.a.s.l. with a mean annual precipitation of 830–1050 mm and a mean annual temperature of 19–22 °C (https://www.meteorwanda.gov.rw, 2023;

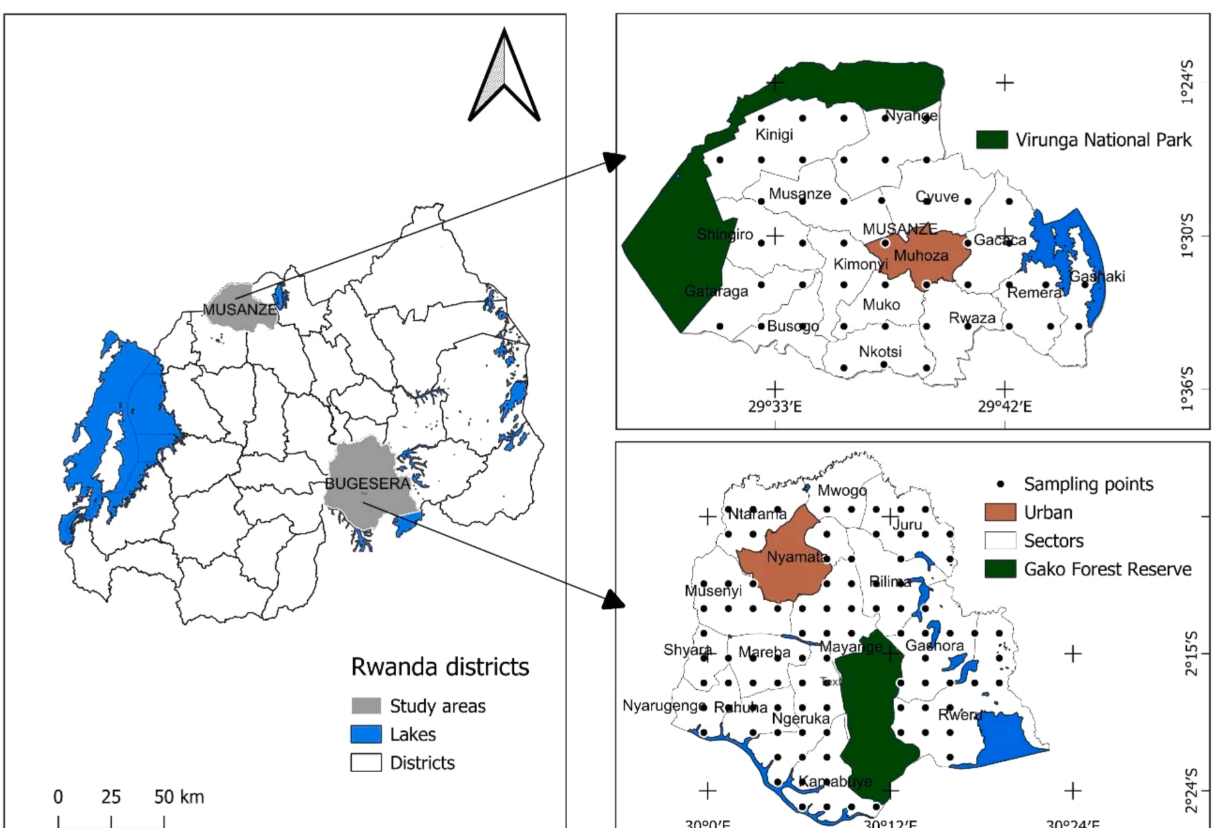

Fig. 1. The map of the study area showing the study regions (gray color) and the location of the band transect (black point).

Bugesera DDP, 2019). The soil of Bugesera is susceptible to drought due to the low rainfall and long dry seasons. The total land of Bugesera is 133,700 ha, with the forests occupying 21,479 ha, agricultural land 84, 631 ha, marshlands and lakes occupying 18,100 ha, and urban areas covering 9690 ha (MoE, 2019; Bugesera, 2019). As per the Bugesera District Development Strategy (DDS 2018/19–2023/24) (2019), the vegetation of this area is typically dominated by the savannahs, shrubs covering the hills, and grassy savannahs covering the dry valleys. Bugesera District has a total population of 551,103 with a density of 427.7 inhabitants/km^2, with the majority working in the agricultural sector (NISR, 2022). The natural vegetation is also primarily composed of acacia trees and *Euphorbia tirucalli* intertwined with grasses and spiny bushes (NISR, 2022).

Musanze is found in the highland areas dominated by high mountains at 2000–4500 m.a.s.l. Musanze experiences an average temperature of 17.7 °C year-round, with April being the warmest and June being the coolest. The district receives an average of 1260–1700 mm of precipitation, with April having the most precipitation and July having the least (https://www.meteorwanda.gov.rw, 2023). The soil of Musanze is very susceptible to erosions and landslides due to the high rainfall (NISR, 2012; Dibanga et al., 2016). The total area of Musanze district is 53,040 ha, where the forests cover 11,616 ha; agricultural land is 30,509 ha; the volcanoes National Park 6000 ha; Lake Ruhondo 2800 ha, and urban areas cover 2115 ha (MoE, 2019; Musanze District, 2017). As per Musanze District Development Strategy (DDS 2018/19–2023/24) (2019), the vegetation comprises food crops and tree species on hillslopes. The district has a total population of 476,522, with a density of 900 inhabitants/km^2, with most of the population working in the agricultural sector (NISR, 2022).

2.2. Sampling design

The study employed a systematic sampling design with a random starting point where transects were established at an equal interval of 3 km. In each district, the starting point of the transect was randomly predetermined using the sampling design tool in ArcGIS 10.4 and traced in the field using GPS Garmin 60CSx.The transects were 5 m wide and 1 km long toward the north and 1 km toward the east. A compass bearing was used to navigate within and between transects. A total of 84 and 46 band transects were established in Bugesera and Musanze Districts, respectively, yielding a total of 130 transects (Fig. 1). We sampled a greater number of plots in Bugesera compared to Musanze due to the larger agricultural landscape of Bugesera relative to Musanze (Bugesera DDP, 2019; Musanze DDP, 2017).

2.3. Tree inventory

The tree inventory was conducted from May to August 2023 in Bugesera District and from September to December 2023 in Musanze District. Along each band transect, all woody tree species were counted, local and scientific names were identified by a botanist, and the age of the trees was provided by the farm owners. The DBH at the breast height (DBH) of each tree was measured using diameter tape, and the height was measured using a Suunto PM5/1520 clinometer. If a tree was coppiced, each coppice was considered an individual stem. Additionally, in each transect, TBS were identified based on criteria presented in Table 1.

The four most common tree species used for fuelwood were considered relevant for the current study and, therefore, selected for detailed analysis. The selected tree species are abundant and commonly used for fuelwood in the study areas (Ndayambaje and Mohren, 2011). Those species are fast-growing coppices and are often preferred for fuelwood supply because they can be harvested more frequently, leading to a sustainable and reliable source of biomass (World Agroforestry Centre, n.d.). In addition, the selected species are well-adapted to the local climate and soil conditions, whereby maintaining them in the agricultural landscape contributes to the sustainability of fuelwood supply (Anywar et al., 2022). The AGB was estimated using the equation developed by Kuyah et al. (2012). The equation was selected because it was developed using Multiple species in Kenya's agroforestry systems, similar to the TBS in Rwanda's agricultural landscape.

Table 1
Description of the criteria used to describe various tree-based systems.

S/N	Tree based system	Criteria for tree-based system
1	Home garden	Trees planted around the family compound predominantly include fruit trees, bananas, ornamental, *Ficus thonningii, Erythrina abyssinica* , Manihot esculenta (isombe), and *Euphorbia tirucalli* .These are primarily cultivated for home consumption and used as compound fences and shading.
2	Boundaries planting	Trees are often planted in a single row to demarcate the boundaries between plot owners. Alternatively, trees might be arranged in broad rows, subdividing the farm into a sequence of slender fields with trees lining each one. Sometimes, two rows of trees are used for delineation, with one row on each side of the boundary; each farmer is responsible for cultivating and managing his/her respective trees. The boundaries planting are primarily made up of *Euphorbia tirucalli* and various shrubs.
3	Mixed cropping	They are referred to as woody perennials grown in association with crops or within/inside the farmland. The system comprises a mixture of banana, coffee, fruit trees, timber trees (*G.robusta*), and nitrogen-fixing trees with biannual crops and annual crops, which together optimize the use of soil, moisture, nutrient replenishments, timber, shade, and space.
4	Live fences	are permanent or semi-permanent structures of trees planted around the farmland or located alongside rural or urban roads. In many places, farmers combine trees such as *Euphorbia tirucalli, Albizia amara, Lantana camara, Dichrostachys cinerea*, some *Eucalyptus spp, G.robusta, S. spectabilis, A.acuminata*, surrounding the farms. Fences are used to mark boundary lines between farms next to roads, protect adjacent fields used for distinct purposes, protect and keep animals from straying, and protect crops from animal damage. In addition, live fences are trimmed or pruned periodically, and the branches are used as fuel leaves, fodder, and fertilizer; live fences provide privacy to the farmland.
5	Woodlots	Trees planted in a small area, typically less than 0.5 hectares, can consist of one or more species. These trees are usually spaced at intervals of 3 x 3 m or even closer. In Bugesera, the most common tree species in these woodlots is *Eucalyptus* spp. and *S.spectabilis*, while in Musanze, it is *Eucalyptus spp*. These woodlots primarily serve the purpose of fuelwoods, timber, and construction. Although livestock grazing can occur within these woodlots, there is no integration with annual crops.

The equation was:

$$AGB = 0.091 \times DBH^{2.472}$$

Where AGB = the estimated aboveground biomass (kg/tree), DBH = the diameter at breast height (cm).

The AGB in kg ha^{-1} was calculated by dividing the AGB per tree by the transect area (1 ha). The AGB was divided by the age of trees to get species productivity in kg ha^{-1} yr$^{-1.}$ The species' productivity was divided by the number of stems to get the productivity of species per tree in kg yr^{-1} tree^{-1}.

The farm's owners provided information on the age of approximately 65% of the trees by indicating when the trees have been planted or since the last tree harvesting. For the remaining 35% of trees whose age was not directly provided, the age was calculated as follows:

1) A mathematical relationship was established between DBH and the available age data for the trees. According to Su et al. (2023), there is a positive association between the age of trees and DBH.

The identification and removal of unrealistic data were done using computational approaches, specifically, the Isolation Forest algorithm performed in Python (Burkhart and Tomé, 2012; Dash et al., 2023; Kershaw et al., 2016; Pretzsch, 2009; Vanclay, 1994; Weiskittel et al., 2011; Wickham, 2014). The linear relationship was then used to estimate the age of the trees where only DBH was known and to model the biomass growth (Fig. 6). The equations used for estimating the missing ages were as follows:

Bugesera

$$G.robusta, Age = 0.4114DBH + 0.2327, withR^2 = 0.9197$$

$$Eucalyptusspp., Age = 0.1918DBH + 1.8549, withR^2 = 0.7141$$

$$S.spectabilis, Age = 0.1324DBH + 0.0763, withR^2 = 0.7049$$

Musanze district

$$G.robusta, Age = 0.4379DBH + 0.9621, withR^2 = 0.9365$$

$$Eucalyptusspp., Age = 0.1975DBH + 1.1504, withR^2 = 0.8905$$

$$A.acuminata, Age = 0.1842DBH + 1.081, withR^2 = 0.91$$

2.4. Data analysis

The tree inventory data were summarized as mean percentages computed in Microsoft Excel software version 2016 (Microsoft Corporation.,2018). As the data does not follow a normal distribution, necessitating a more resilient analytical approach without strict parametric assumptions, the non-parametric Kruskal-Wallis was used to determine if there were significant differences in AGB and stem density of species across different TBS categories (Rodriguez-Galiano et al., 2012). Subsequently, the post hoc Dunn test was carried out to find the specific differences in AGB and stem density of species among the various TBS categories. The statistical significance level was adopted at $p < 0.05$. Furthermore, curvilinear regression was applied to model the relationship between AGB per tree and the tree's age to assess biomass productivity in short rotation (5 years) (Charru et al., 2012; Picard et al., 2015; Cao et al., 2016).

The mean number of stems for each selected species and the DBH class distribution were determined using IBM SPSS Statistics (Version 27) (IBM Corp.,2020). The Kruskal-Wallis Test and curvilinear regression were performed using R software (R Core Team, 2022).

3. Results

3.1. Floristic composition and distribution of tree species

A total of 6251 trees from 45 different species were identified in Bugesera, while 6081 trees from 46 species were found in Musanze District (Electronic supplementary material Table 1). In Bugesera District, the common tree species utilized were *Eucalyptus* spp., *S.spectabilis, M.lutea*, and *G.robusta* (Fig. 2a). Meanwhile, in Musanze District, the common tree species for fuelwood use were *Eucalyptus* spp., *A.acuminata, M.lutea*, and *G.robusta* (Fig. 2b). While *S.spectabilis* was frequently found in Bugesera, it was rare in Musanze District. *A.acuminata* was common in Musanze but not present in the Bugesera District.

A large proportion of the observed stems for all species except *G. robusta* were coppices (Fig. 3). Considering the size characteristics, the large proportion of *Eucalyptus* spp. fell within the 5.1–10 cm DBH class. In contrast, a large proportion of both *M.lutea* and *A.acuminata* were found with a 1–5 cm DBH class. Most stems of *G.robusta* were in the 10.1–15 cm and 15.1–20 cm DBH classes. Only two species, *G.robusta* and *Eucalyptus* spp., were found in the 25.1–30 cm and over 30 cm DBH classes (Fig. 4).

In Bugesera District, a large majority of trees across all TBS were classified with 1–5 cm DBH class, with the only exception being the woodlot, which had a substantial proportion of trees in the 5.1–10 cm DBH class (Fig. 5a). Conversely, in Musanze District, most trees across all TBS predominantly fell within the 5.1–10 cm DBH class (Fig. 5b.). Furthermore, in Bugesera, a substantial number of larger trees, specifically those with DBH ranging from 20.1 to 30 cm and beyond 30 cm, were found in mixed cropping areas and boundaries. However, in Musanze, the larger trees were found in boundaries and woodlots. Across all TBS, the number of individual trees decreased as the tree size (DBH) increased.

3.2. Variation of stem density, aboveground biomass of trees across various tree-based systems

The summary of the average stem density and AGB across different TBS is presented in Table 2. In Bugesera District, the average stem density and AGB per hectare were significantly higher in boundary plantings and mixed cropping areas compared to live fences, woodlots, and home gardens. However, in Musanze District, the average number of stems and AGB were significantly higher in boundary plantings and woodlots than in live fences and home gardens. For both districts, home gardens recorded the least stem density.

Regarding species, *Eucalyptus* spp. and *S.spectabilis* had higher stem density than the other species in Bugesera District, while in Musanze District, the highest stem density and AGB were recorded in *Eucalyptus spp*. In contrast, *G.robusta* and *S.spectabilis* recorded significantly greater

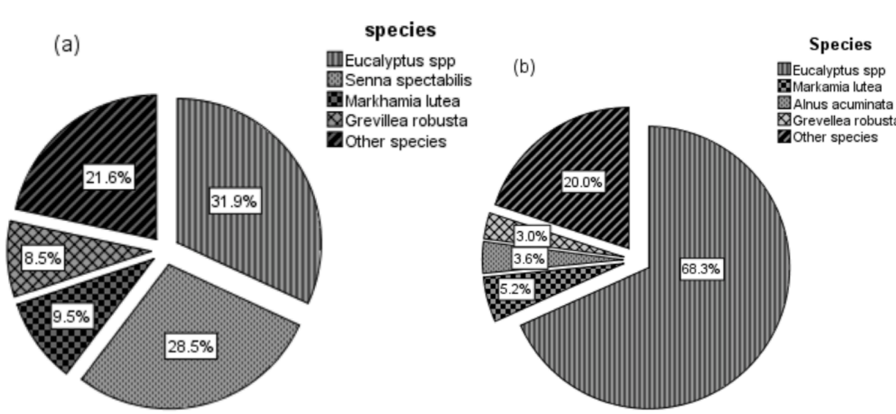

Fig. 2. The proportions of different tree species in two districts covering (a) Bugesera District and (b) Musanze District. Other species cover the remaining species, including fruit trees, *Euphobia triculli, Dichrostachys cinerea,* and medicinal trees in the landscape, which are not commonly used as fuelwood.

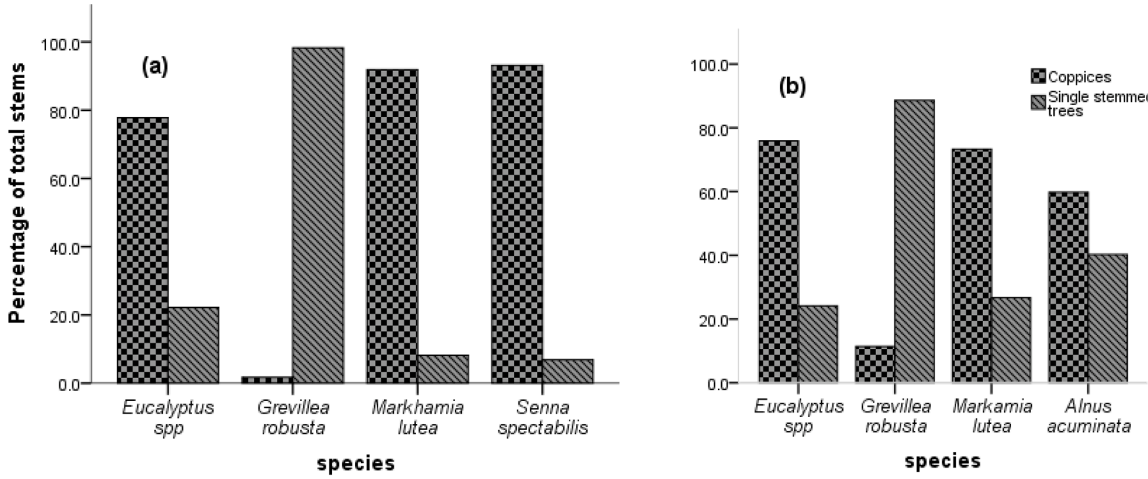

Fig. 3. The proportion of single-stemmed trees and coppices in Bugesera(a) and Musanze (b).

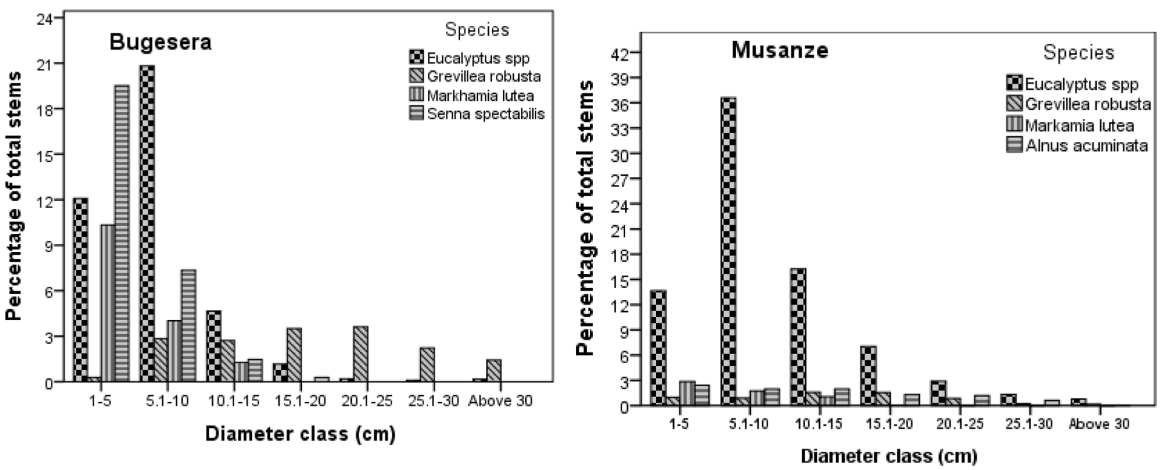

Fig. 4. DBH size distribution of the common tree species for fuelwood use in Bugesera and Musanze Districts.

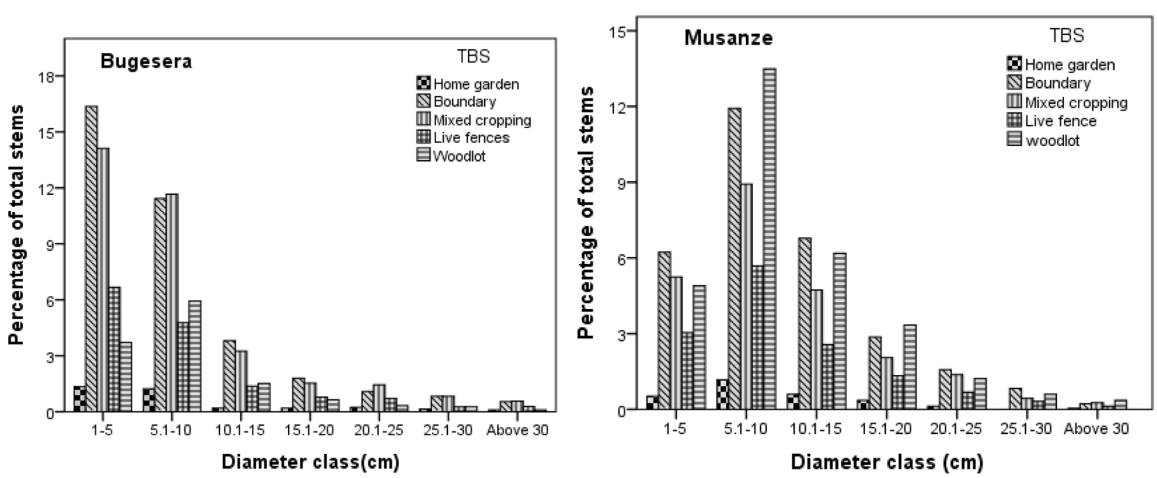

Fig. 5. DBH size distribution of the common tree species for fuelwood use across various tree-based systems.

AGB than the other species in Bugesera District (Table 3). *M.lutea* displayed the lowest stem density and AGB in both districts (Table 3).

3.3. *Productivity across various tree-based systems and species*

In Bugesera District, boundary plantings and mixed cropping trees were significantly more productive than trees in the other TBS (Table 2). Furthermore, *S.spectabilis* were more productive (Table 3). In Musanze

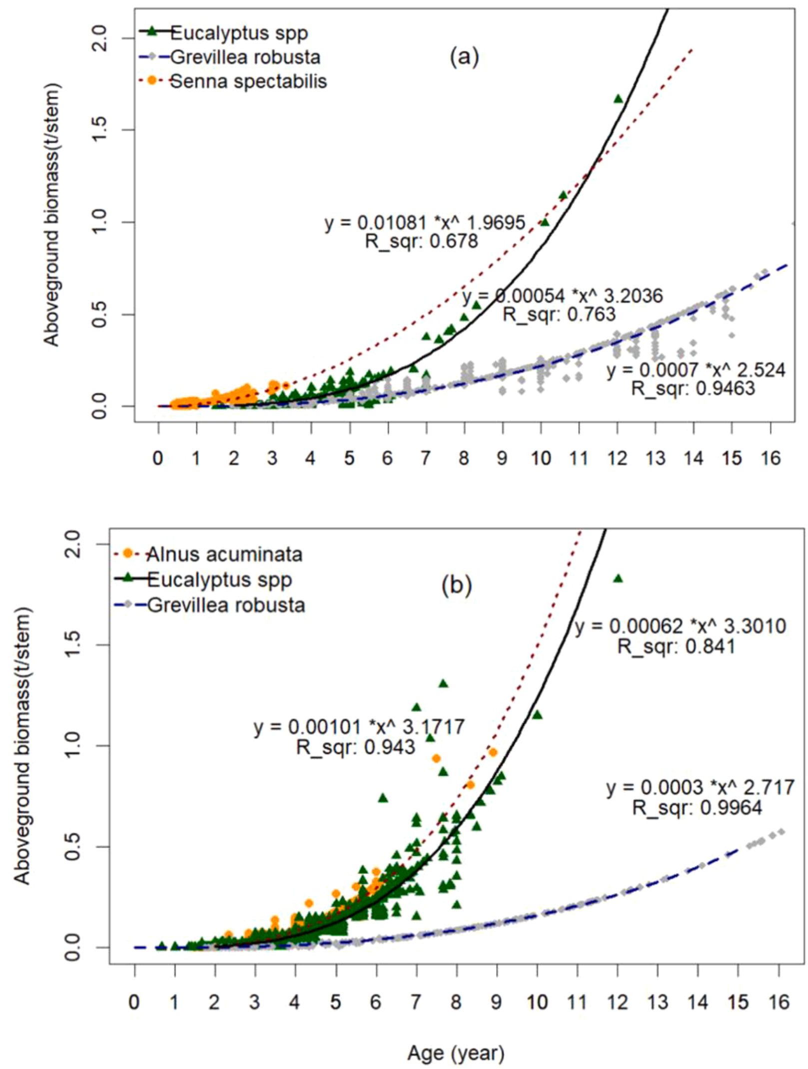

Fig. 6. The change of aboveground biomass of the common tree species for fuelwood use with age in (a) Bugesera and (b) Musanze. Whereby R_sqr = R2, Y: is the aboveground biomass in t/stem), Moreover, x is the age of the tree (year).

Table 2
Summary of the mean number of stems and aboveground biomass of various tree-based systems in Bugesera and Musanze Districts .

TBS	**Bugesera** (Mean±SE)			**Musanze** (Mean±SE)		
	Stems n/ha	**AGB t/ha**	**AGB (t/ha/year)**	**Stems n/ha**	**AGB t/ha**	**AGB (t/ha/year)**
Home garden	1.73± 0.42[c]	0.10± 0.03[b]	0.01±0.00[c]	3.07±0.76[c]	0.13±0.04[c]	0.03±0.00[d]
Boundary planting	18.05±1.85[a]	0.73±0.08[a]	0.13±0.02[a]	33.26±3.71[a]	1.71±0.22[a]	0.32±0.11[a]
Mixed cropping	16.81±1.45[a]	0.71±0.09[a]	0.12±0.01[a]	25.17±4.28[ab]	1.23±0.21[ab]	0.26±0.08a[b]
Live fence	7.48±1.06[b]	0.31±0.07[b]	0.06±0.01[b]	15.02±2.34[bc]	0.71±0.14[bc]	0.13±0.03[c]
Woodlot	6.28±0.94b[c]	0.22±0.05[b]	0.04±0.00[bc]	32.89±3.40[a]	1.60±0.21[a]	0.35±0.11[a]

Means followed by the same letter in the lower-case column do not differ from each other in the same column ($p < 0.05$).

Table 3
Summary of the mean number of stems (n/ha), AGB (t/ha), and AGB productivity (t/ha/year) of different species in two districts .

Species	**Bugesera** (Mean±SE)			**Musanze** (Mean±SE)		
	Stems (n/ha)	**AGB (t/ha)**	**AGB(t/ha/year)**	**Stem (n/ha)**	**AGB(t/ha)**	**AGB(t/ha/year)**
Eucalyptus spp.	19.71± 2.20[a]	0.41± 0.05[b]	0.09±0.02[b]	85.84±8.76[a]	3.82±0.43[a]	0.86±0.14[a]
G.robusta	8.36±0.78[b]	1.50±0.14[a]	0.12±0.03[a]	6.87±1.01[b]	0.65±0.10[b]	0.08±0.03[b]
M.lutea	7.87±1.02[b]	0.07±0.01[c]		6.26±1.33[b]	0.09±0.02[b]	
S.spectabilis	14.40±1.52[a]	0.12±0.01[c]	0.15±0.02[a]	–	–	
A.acuminata	–	–		10.43±1.41[b]	0.81±0.12[b]	0.15±0.04[b]
Total	50	2.07	0.36	109	5.38	1.09

Means followed by the same letter in the upper-case column do not differ from each other in the same column ($p < 0.05$).

District, woodlots and boundary plantings were significantly more productive than trees in home gardens and live fences but comparable to mixed cropping (Table 2). Unlike Bugesera, *Eucalyptus* spp. was substantially more productive than *G.robusta* (Table 3).

Graph 6 illustrates the relationship between aboveground biomass and the age of the tree species. The regression equations and R^2 values offer valuable insights into the strength of this relationship for each species. The observed positive correlation between aboveground biomass and age, as indicated by the R^2 values, suggests that as the age of trees increases, their aboveground biomass tends to increase. The aboveground biomass at the young growth stage varies among species, with *Eucalyptus* spp. and *S.spectabilis* showing a relatively rapid increase in biomass within five years in Bugesera District (a) while *Eucalyptus* spp. and *A.acuminata* showing a relatively faster growth rate in Musanze district (b).

4. Discussion

The results of this study indicated that the tree species commonly used for fuelwood were *Eucalyptus* spp., *S.spectabilis, M.lutea*, and *G. robusta* in Bugesera District, and *Eucalyptus* spp., *A.acuminata, M.lutea*, and *G.robusta* in Musanze District. The dominance of *Eucalyptus* spp.*, M. lutea,* and *G.robusta* in both districts can be explained by their adaptability in various climatic conditions and the range of ecosystem services they provide (Hassan et al., 2021). The dominance of *S.spectabilis* in Bugesera District is due to its adaptability to semi-arid areas and the provision of fuel wood in short rotation (Iacopino et al., 2022). *S.spectabilis* is sensitive to waterlogging in high-rainfall areas, which often occurs in Musanze District (Cassino et al., 2023). On the other hand, *A. acuminata* grows well in high-rainfall areas at cooler elevations with abundant moisture, explaining its dominance in the Musanze district (Cyamweshi et al., 2021).

The most common species used for fuelwood in all TBS categories had DBHs ≤10 cm, whereby the high number of stem densities were coppices, except for *G.robusta*. The farmers regularly harvest the trees planted in the agricultural landscape to reduce the competition with crops on light, water, and nutrients (Vyamana et al., 2023). On the other hand, the balance between single-stemmed trees and coppices might influence the area's overall biomass and regenerative capacity (Cao et al., 2016). Coppicing, a method where trees are cut back to ground level periodically to encourage new growth, can be a sustainable way of harvesting wood without destroying the tree (McKenney et al., 2014). The prevalence of this practice might indicate local strategies for sustainable fuelwood production (Wicke et al., 2011). Furthermore, managing smaller trees is more practical and efficient for regular harvesting, which promotes a more balanced and productive system, especially in fuelwood scarcity areas like Rwanda (Oriwo et al., 2023). Additionally, the small and medium DBH sizes provide more biomass for fuelwood due to their much higher stem densities than big-sized trees (Vyamana et al., 2023). On the other hand, the presence of big tree sizes of *G. robusta* was explained by keeping *G.robusta* longer in the farms for timber production (Cyamweshi et al., 2021).

The average stem tree density recorded in our study was 50stems/ha in Bugesera and 109 stems /ha in Musanze, with an overall average stem density recorded in this study of 79.5 stems/ha in the two districts (terrestrial sampling), which is similar to 79.6 trees/ha found by using remote sensing (Mugabowindekwe et al. (2022). The difference in stem density among districts is attributable to the difference in the agroecological condition and species adaptability. The moist and temperate climate of Musanze promotes the growth of Eucalyptus trees, which in turn leads to a higher stem density than other species (Mugunga, 2016). On the other hand, the semi-arid environment of Bugesera supports the growth of drought-resistant *S.spectabilis*, resulting in a greater stem density than other species (Marc, 2020). The stem density is critical for understanding how different tree-based systems contribute to biomass production (Eufrade et al., 2016). Systems with higher stem density and biomass might be more suitable for fuelwood production (Mukuralinda et al., 2021). However, the ecological impact of each system, such as biodiversity support or soil health, must also be considered to balance productivity with sustainability (Sassen et al., 2015). In this study, the average stem density and AGB across different TBS were substantially higher in boundary plantings and mixed cropping at Bugesera, while in Musanze district, the stem density and AGB were substantially higher in woodlot and boundary planting compared to live fences and home gardens. The low stem density in the live fences and home garden in both districts is due to most of the trees used in the live fences, and home garden are not used for firewood and thus were excluded from the analysis (Ahmad et al., 2020; Mengistu and Asfaw, 2016). The high stem density in boundary plantings is due to farmers planting many trees to mark or divide the farm boundaries between two farm owners (Fuchs et al., 2022). The *Eucalyptus* spp. had higher mean stem density than other species in both districts. In contrast, *M.lutea* displayed low stem densities and registered the lowest AGB in both districts. *Eucalyptus* is known for its ability to adapt to various climatic conditions from tropical to temperate regions but is more productive in high rainfall areas. Also, when regularly cut, Eucalyptus resprout more coppices in a short time (Resquin et al., 2022). The high stem density of *S.spectabilis* recorded in Bugesera district is due to the capacity for fast-coppicing, with more than five coppices, and trees that are fifty years old may still be coppiced (Hammar et al., 2017; Iacopino et al., 2022). A study conducted in Uganda by Mungatana (2012) indicated that households with *S.spectabilis* gather significantly more firewood annually than those without *S. spectabilis* in their farms. According to Kralik et al. (2022), the number of coppice shoots that emerge from a single stump of *S.spectabilis* quickly helps the farmers get fuelwood in short rotation. The low stem density of *M.lutea* in both districts can be explained by the fact that most indigenous tree species are selectively logged without proper management practices, which can negatively impact their population density (Cernansky, 2015). The same as introducing exotic species outcompete indigenous tree species for resources such as sunlight, water, and nutrients. This competition may result in a decline in the stem density of indigenous trees as they struggle to compete (Timko and Kozak, 2016).

The results show the relationship between aboveground biomass (t/stem) and age (years) for different tree species to estimate the growth rate and productivity of the species. The R^2 values highlight a strong positive correlation, indicating a more predictable relationship between age and aboveground biomass for the tree species represented. In Bugesera District, the comparison involves *Eucalyptus* spp.*, G.robusta*, and *S.spectabilis*. The curvilinear regression analysis revealed that *S. spectabilis* and *Eucalyptus* spp. could produce higher biomass in a shorter time (e.g., five years) than *G.robusta* in Bugesera District (Marc, 2020). In Musanze District, *Eucalyptus* spp. and *A.acuminata* have a higher potential to produce more biomass in the short term (Cyamweshi et al., 2021; Mugunga, 2016). These findings are of considerable significance as they contribute to a deeper understanding of the growth patterns of these specific tree species, which is crucial for informed forest management, ecological modeling, and conservation strategies (Chidumayo, 2019). Understanding how biomass accumulates over time is essential for planning harvest cycles and ensuring a continuous fuelwood supply (Köhl et al., 2017). This data can inform policies on the optimal age for harvesting different species, balancing the need for fuelwood with the growth and health of the forests (Van Holsbeeck et al., 2016). Notably, most trees examined in our study were coppices under five years, indicating that the choice of species to be planted or retained for fuelwood supply might depend on its ability to provide biomass in a short rotation and fast coppices with more coppices after harvesting (Vyamana et al., 2021).

This study has some limitations whereby the age provided by the farmers was used to estimate productivity, for which the farmers could not always give accurate tree age, which was back-calculated from DBH and age from the trees for which the age was provided. Although our results do not indicate it, we acknowledge that the growth of coppices respectively planted trees, could differ over extended periods from the age of trees in our study.

5. Conclusion

This study offers valuable information on the size, stem density, aboveground biomass (AGB), and productivity of commonly used species for fuelwood supply across TBS in agricultural landscapes of Bugesera and Musanze Districts in Rwanda. The research identifies various tree species commonly used for fuelwood, with *Eucalyptus* spp., *S.spectabilis, M.lutea,* and *G.robusta* were the dominating species in the Bugesera District, while in Musanze District, *Eucalyptus* spp., *A.acuminata, M.lutea,* and *G.robusta* were dominating species. Moreover, the results indicated that farmers prefer smaller tree DBH (≤10 cm) for fuelwood, as they do not compete significantly with crops for resources in the agricultural landscape. However, with a larger DBH, *G.robusta* is maintained for timber production and pruned for fuelwood supply. The productivity assessments revealed that boundary plantings and mixed cropping were more productive in Bugesera, whereas woodlots and boundary plantings were more productive in Musanze District, indicating the importance of these tree-based systems for biomass production. The correlation analysis of aboveground biomass and age of tree species revealed significant relationships between these two parameters, indicating the developmental patterns and productivity of different tree species. The study identified strong correlations between AGB and age for specific tree species, highlighting the potential for using these relationships in TBS management and species selection. The observed correlations provide valuable insights into tree species growth trajectories and the productivity potential of tree species, offering opportunities for optimizing tree species and promoting sustainable resource management. By understanding the AGB-age relationship, practitioners and policymakers can make informed decisions regarding tree species selection and agroforestry management practices, ultimately contributing to environmental sustainability and ecosystem resilience. Species-specific productivity variations were observed, with *S.spectabilis* in Bugesera District and *Eucalyptus* spp. and *A.acuminata* in Musanze District being more productive in short rotation than other species. This study underscores the potential of on-farm fuelwood production, providing sustainable fuelwood supply while alleviating pressure on natural forests through integrated tree-based systems in the agricultural landscape. Overall, this research contributes significantly to understanding the dynamics of tree species commonly used for fuelwood, guiding landscape restoration management strategies tailored to specific species and tree-based systems, and highlighting the importance of short-rotation coppice systems for sustainable biomass production in fuelwood supply.

CRediT authorship contribution statement

Elias Nelly Bapfakurera: Writing – original draft. **Jean Nduwamungu:** Writing – review & editing, Supervision, Methodology. **Gert Nyberg:** Supervision, Conceptualization. **Charles Joseph Kilawe:** Supervision.

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.

Data availability

Data will be made available on request.

Acknowledgement

The authors acknowledge the funding provided by Sida under grant number 13394 to the Regional Research School in Forest Sciences (REFOREST), College of Forestry, Wildlife, and Tourism, Sokoine University of Agriculture, P.O. Box 3009 Chuo Kikuu, Morogoro, Tanzania.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.tfp.2024.100552.

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