

IMPACT OF PROJECT INTERVENTIONS ON TREE DIVERSITY AND BIOMASS PRODUCTION IN AGROFORESTRY FARMS IN KAYONZA DISTRICT, EASTERN PROVINCE OF RWANDA

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ABSTRACT

*Agroforestry has gained recognition as a nature-based strategy for building climate resilience, rehabilitating degraded lands, and improving the livelihoods of small-scale farmers. Despite this, there is insufficient empirical data on how agroforestry projects affect tree species diversity, stocking density, and biomass accumulation. This study assessed tree and shrub diversity, stocking density, and aboveground biomass across different agroforestry practices in Kayonza District, Eastern Rwanda, comparing project intervention sites supported by the LDCF II Ecosystem-based Adaptation approach project with no intervention areas. Using systematic band transects covering 26 sampling units, all woody species were inventoried and measured for diameter and height, and aboveground biomass was estimated using an allometric equation. A total of 39 species was recorded in no-intervention areas and 36 species in intervention areas, with both systems dominated by a small number of widely preferred species, including *Eucalyptus* spp., *Grevillea robusta*, *Mangifera indica*, *Persea americana*, *Euphorbia tirucalli*, and *Senna* spp. Tree and shrub density was four times higher in intervention areas (172 stems ha⁻¹) than in non-intervention areas (43 stems ha⁻¹), while diameter class distributions were dominated by small trees (< 10 cm DBH) in both zones. Despite smaller average tree sizes, intervention areas exhibited substantially higher above-ground biomass (15.33 t ha⁻¹) compared to no-intervention areas (4.51 t ha⁻¹), largely due to higher stocking density and wider adoption of biomass-efficient practices. Scattered trees on farm consistently ranked highest in biomass contribution across both zones. These findings demonstrate that targeted agroforestry interventions can rapidly enhance landscape-level biomass and carbon sequestration potential, even at early stages of tree establishment. To sustain and maximize these benefits, future interventions should prioritize agroforestry practice diversification, adaptive management, greater integration of native species and long-term monitoring to balance productivity, biodiversity, and income.*

Key words: project interventions, agroforestry species, aboveground biomass, agroforestry practices, agroforestry systems in Rwanda

INTRODUCTION

The increasing greenhouse gas emissions since the 19th century have intensified global warming and climate change, leading to more frequent and severe extreme weather events worldwide (Collier *et al.*, 2008; Wheeler and Von Braun, 2013). East Africa is particularly vulnerable to these impacts, experiencing prolonged droughts and floods that threaten rain-fed agriculture, the main livelihood for ca. 80% of the population (East African Community, 2011; UNECA, 2017). Rwanda, as part of East Africa, faces serious challenges due to successive droughts, heavy rainfall,

and widespread environmental degradation caused by unsustainable land use, population pressure, and steep topography (Li *et al.*, 2021; REMA, 2021). These conditions have led to reduced agricultural productivity, food insecurity, and biodiversity loss (Gupta, 2019; Dagar *et al.*, 2020). Ecosystem restoration and sustainable management, especially through Ecosystem-based Adaptation (EbA) strategies such as agroforestry, is widely recognised as an effective approach to build resilience, enhance the delivery of ecosystem services, and ensure food security (USAID, 2019; UNDP, 2023).

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Agroforestry contributes to the achievement of many Sustainable Development Goals (SDGs), including SDG 2 (zero hunger), 13 (climate action), and 15 (life on land), through its impact on increasing agricultural production and climate resilience (FAO and UNEP, 2020). In this context, Rwanda has prioritised agroforestry in its land restoration efforts and committed to restoring two million hectares of degraded land by 2030 under the Bonn Challenge. That is why the Government of Rwanda adopted a national agroforestry strategy and action plan to support agroforestry development (Regreening Africa, 2023).

However, limited research has focused on tree species diversity, resilience, and growth performance in the various agroforestry practices, prompting the current study to assess on-farm tree stocking and species diversity in savannah tree-based systems in Kayonza district, Eastern Rwanda. The study conducted an inventory to assess the richness of tree species and stock dynamics in agroforestry systems within project intervention and no intervention zones to evaluate the impact of the Ecosystem-based Adaptation (EbA) project on landscape restoration. The project entitled “*Building resilience of communities living in degraded forests, savannahs and wetlands of Rwanda through an AbA approach*”, hereafter denoted “LDCF II project”, was funded by the Global Environment Facility (GEF)/Least Developed Countries Fund (LDCF II). It was implemented by Rwanda Environmental

Management Authority (REMA) from Sep. 2016 to Dec. 2023. The project has been implemented in Kayonza, Kirehe, Bugesera, Gasabo, Ngororero, and Musanze Districts. Among other achievements in Kayonza district, the LDCF II project has successfully restored and rehabilitated Kibare lakeshores through bamboo planting and agroforestry practices on 80 ha, and fruit trees planting on 32 km in Ndego Sector and Rwinkwavu sectors. This study sought to assess tree species composition and stocking density and aboveground biomass in different agroforestry systems within project intervention and no intervention zones to gauge the contribution of agroforestry tree species to landscape restoration and climate resilience in Rwanda.

MATERIALS AND METHODS

Description of the Study Area

Kayonza District in Eastern Province of Rwanda (1°51'0" S; 30°39'0" E), covering approximately 1,954 km², is characterized by semi-arid conditions, relatively low elevations (1,400-1,600 m), and a wet tropical climate with two dry and two wet seasons. The mean annual temperatures range between 18°C and 26°C, and rainfall in the range of 1,000-1,200 mm (Kayonza, 2018). Kayonza district borders with Gatsibo district in the North, Kirehe and Ngoma districts in the South-East, Rwamagana district in the West, and the Republic of Tanzania in the East (Muhoza *et al.*, 2023) (Figure 1).

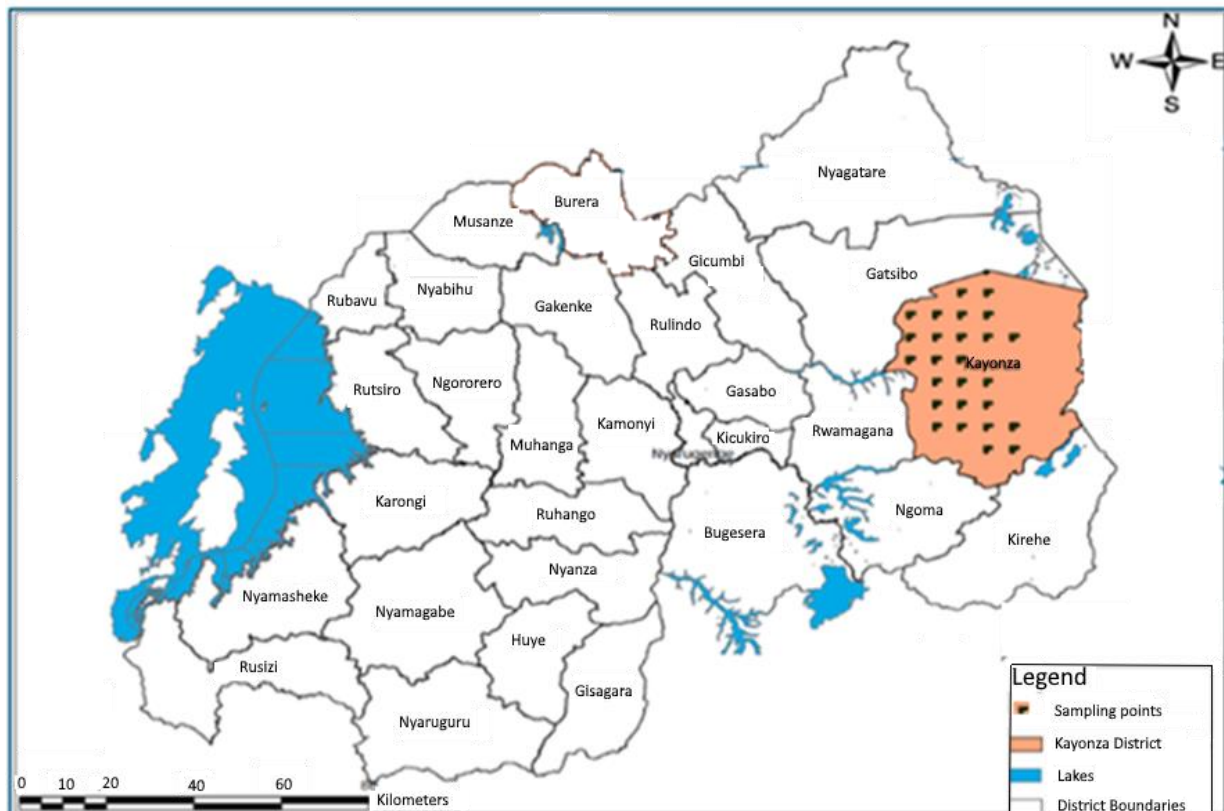


Figure 1: The study area in Rwanda showing the location of sampling points

Kayonza district is predominantly characterized by savanna vegetation, which is shaped by the region's relatively low rainfall and high temperatures. The district is part of the savanna woodland and bushland zone that extends across Rwanda's eastern province. The district is mainly covered with mixed vegetation classes including croplands, grasslands, shrublands, and woodlands. Both exotic and remnant indigenous (native) tree and shrubs species are found throughout the agricultural areas in both intervention and no intervention zones. The most prevalent agroforestry system is agrisilvopastoral with various agroforestry practices that were identified in this study.

Sampling Design

The study employed a systematic sampling design with a randomly selected starting point, where band transects were laid out at 5 km intervals. The initial transect location was randomly generated using the sampling design tool in ArcGIS 10.8 and then located in the field using a Garmin GPS 60CSx. A compass bearing was used to guide navigation within and between transects. To obtain data for this study, agroforestry and land use/cover data were collected along 26 random transects in Kayonza District. The transect was 5 m wide and extended 1 km to the North and 1 km to the East and thus covered an area of 1 ha. Each transect consists of two wings, one oriented North–South and the other East–West (Figure 2).

Agroforestry Tree Inventory

The tree inventory in the laid out band transects was carried out at the end of the rainy season. Within each band transect, all woody tree species were identified (both local and botanical names) and measured for diameter and height. The diameter at breast height (DBH) of each tree was measured using a diameter tape, and the height was measured using a Suunto PM5/1520 clinometer. For coppicing trees, each coppice was considered as an individual stem. The above-ground biomass (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, which is similar to the tree-based system (TBS) in Eastern Rwanda's agricultural landscape, based on climate conditions, including temperature and rainfall. The equation was:

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

where AGB is the estimated above-ground biomass (kg tree⁻¹), DBH is the diameter at breast height (cm), measured at 1.3 m from the ground.

The AGB in kg ha⁻¹ was calculated by dividing the sum of AGB per tree by the transect area (1 ha). The six most dominant tree species were considered relevant for further detailed analysis in different agroforestry system practices. These tree species are abundant and commonly used for fuelwood in the study area, while others are fruit trees (Ndayambaje and Mohren, 2011).

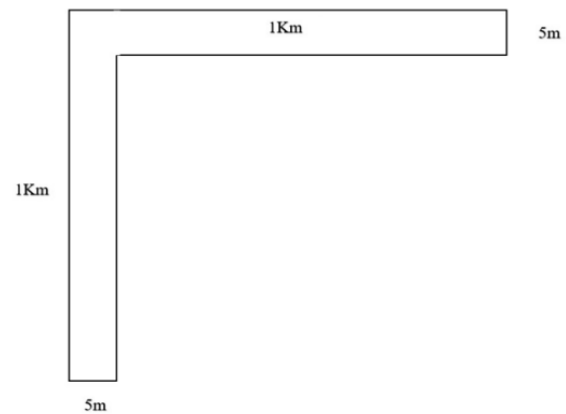


Figure 2: Transect band used as a sampling unit

Data Analysis

Tree inventory data were summarised as mean percentages computed in Microsoft Excel software version 2016. As the data do not follow a normal distribution, a more resilient analytical approach without strict parametric assumptions was required. So, a nonparametric Kruskal-Wallis test was used to identify specific differences in DHB and stem biomass among species within the various agroforestry system practices. The Kruskal-Wallis test was performed using IBM SPSS Statistics (Version 27). The mean number of stems and the distribution of DBH classes were also determined using IBM SPSS Statistics (Version 27).

RESULTS

Dominant Tree and Shrub Species Composition

In total, 39 different tree and shrub species (18 exotic and 21 native species) were inventoried and identified in agroforestry systems within the no project intervention areas. The most dominant tree species in agroforestry systems were *Eucalyptus* spp, *Grevillea robusta*, *Combretum molle*, *Euphorbia tirucalli*, *Persea americana*, *Markhamia lutea*, and *Mangifera indica* (Figure 3).

Trees and Shrubs Stocking and Diameter Classes

Tree and shrub density in the project intervention zone was 172 stems ha⁻¹, while in no intervention zone the observed tree and shrub density was 43 stems ha⁻¹. The highest proportion of inventoried trees and shrubs were small (with a DBH < 10 cm) in both project intervention and no intervention zones. Size distribution of trees and shrubs did not differ much in both project intervention and no intervention zones, although there were relatively more larger trees in the no intervention zone and more trees in DBH class 5.1-10 cm within the project intervention zone (Figure 5).

In the project intervention areas, 36 different tree and shrub species were inventoried and identified. The dominant species were *Senna* spp., *Euphorbia tirucalli*, *Grevillea robusta*, *Eucalyptus* spp., *Vernonia amygdalina*, *Mangifera indica*, and *Persea americana* (Figure 4).

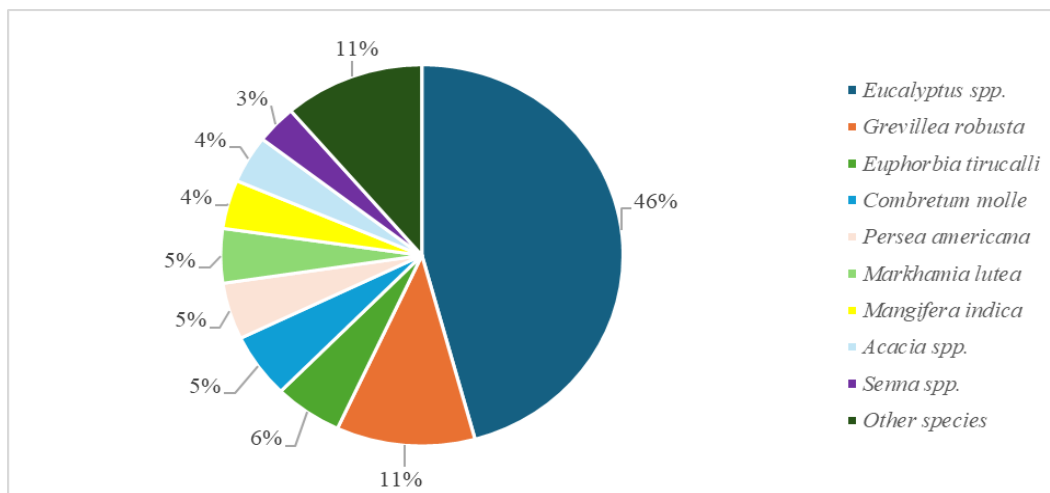


Figure 3: Dominant tree and shrub species inventoried in the no project intervention areas

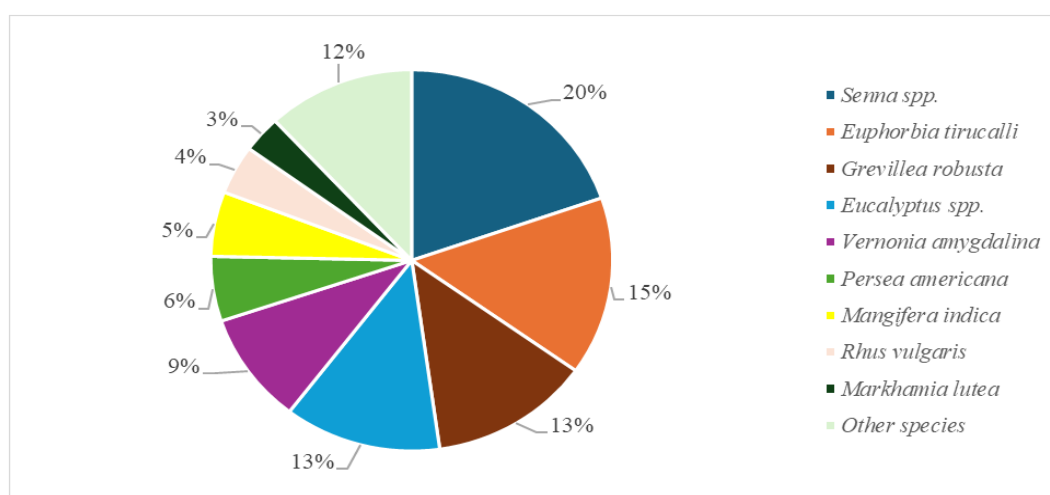


Figure 4: Dominant tree and shrub species inventoried in the project intervention areas

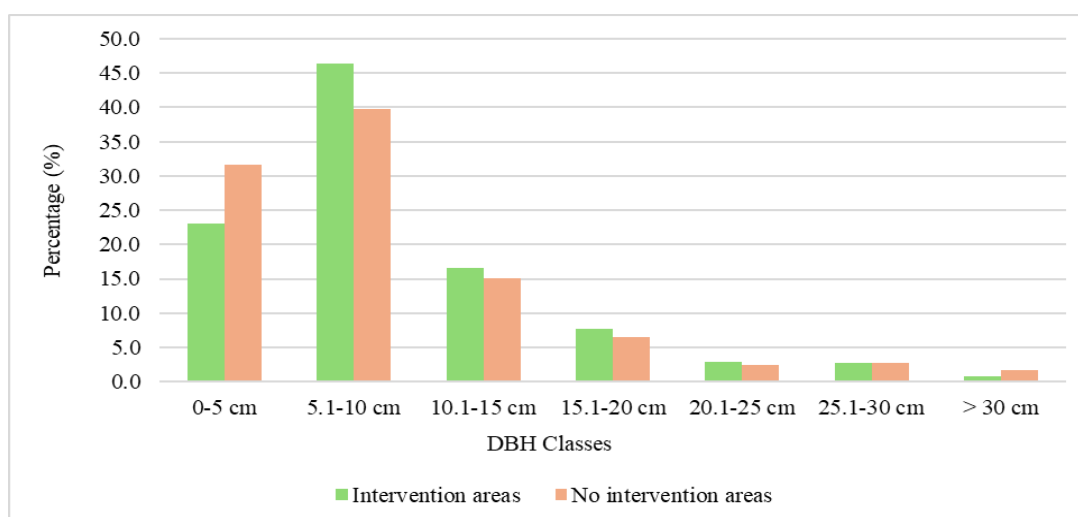


Figure 5: DBH classes distribution in intervention and no intervention zones

Trees and Shrubs Aboveground Biomass Distribution in Agroforestry Practices

The most dominant agroforestry practices observed in project intervention areas were scattered trees on farm (42.2%), while in no intervention zone, small woodlot (40%) was the most common agroforestry

practice (Table 1). The average tree biomass in the project intervention zone was 15.33 t ha⁻¹, whereas that in the no-intervention zone was only 4.51 t ha⁻¹. Scattered trees on farm had the highest tree biomass in both the intervention and no intervention zones, averaging 6.7 and 1.2 t ha⁻¹, respectively (Table 1).

Table 1: Trees and shrubs biomass distribution in agroforestry practices

Agroforestry practice	Project intervention areas		No-intervention areas	
	Percent of trees (%)	Above ground biomass (kg ha ⁻¹)	Percent of trees (%)	Aboveground biomass (kg ha ⁻¹)
Scattered trees on farm	44.2	6735.7	36.1	1246.8
Home garden	17.3	3094.6	1.8	62.8
Intercropping	15	1354.5	9	261.7
Roadside trees	5.5	1069	0.4	22
Boundary planting	11.3	952.4	5.3	162.1
Small woodlots	6.5	229.2	40.5	391.4
Silvopastoral	-	-	6.6	80.1
Others	0.2	3.1	0.3	1.1

Across all agroforestry practices, project intervention sites had generally smaller DBH (Figure 5) and aboveground biomass (AGB) per stem than no intervention sites (Table 2). For example, in home-gardens, *Grevillea robusta* had an average of 65.1 kg stem⁻¹ in project intervention areas, while it had an average of 181.7 kg stem⁻¹ in no intervention areas (Table 2). *Persea americana* had also the same

trend with 51.7 kg stem⁻¹ in project intervention areas and 185.8 kg stem⁻¹ in no intervention area (Table 2). In both intervention and no intervention sites, *Grevillea robusta*, *Persea americana* and *Mangifera indica*, were most frequent and had the highest biomass in home gardens and scattered trees on farm, while *Euphorbia tirucalli* and *Grevillea robusta* were abundant in boundary planting (Table 2).

Table 2: Dominant trees and shrub species size and biomass by agroforestry practices

Practice	Species	Project intervention zone				No intervention zone			
		DBH (cm)		AGB (kg stem ⁻¹)		DBH (cm)		AGB (kg stem ⁻¹)	
		Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.
Home garden	<i>Eucalyptus spp</i>	8	2	19	10.5	0.0	0.0	0	0
	<i>Euphorbia tirucalli</i>	9	0	20.5	2.1	0.0	0.0	0	0
	<i>Grevillea robusta</i>	12.1	6.2	65.1	72.3	21.4	3.7	181.7	75.3
	<i>Mangifera indica</i>	9.7	2.7	28.1	19.9	16.9	1.8	100.6	27.1
	<i>Persea americana</i>	11.1	5.9	51.7	59.3	20.9	7.6	185.8	150
	<i>Senna spp</i>	0	0	0	0	7.9	3.3	18.5	17.5
Intercropping	<i>Eucalyptus spp</i>	18	0	108	0	8.8	4.8	31.4	61.7
	<i>Euphorbia tirucalli</i>	11.3	5.3	51	60.2	4.5	0.0	3.8	0
	<i>Grevillea robusta</i>	8.9	3	24.5	19.4	11.6	5.1	52.1	51
	<i>Mangifera indica</i>	6.5	0.7	10.5	2.1	9.5	5.1	35.7	44.9
	<i>Persea americana</i>	0	0	0	0	12.6	8.8	92.1	174.8
	<i>Senna spp.</i>	6	0	9	0	0.0	0.0	0	0
Boundary planting	<i>Eucalyptus spp.</i>	0	0	0	0	9.3	0.0	22.6	0
	<i>Euphorbia tirucalli</i>	11.5	4.3	47.5	55.8	6.4	2.2	10.9	11
	<i>Grevillea robusta</i>	11.1	3.4	39.6	25.8	10.5	4.5	39.7	39.6
	<i>Mangifera indica</i>	10.4	1.1	32	8.4	0.0	0.0	0	0
	<i>Persea americana</i>	27	0	303	0	14.2	0.2	63.7	2.4
	<i>Senna spp.</i>	9.3	2.8	24.5	15.4	0.0	0.0	0	0
Scattered trees	<i>Eucalyptus spp</i>	14	7.7	95.5	146.5	8.2	6.9	41.2	95.6
	<i>Euphorbia tirucalli</i>	12.3	4.4	57.8	62.3	11.4	8.0	72.5	119.5
	<i>Grevillea robusta</i>	12.6	4.6	60.5	60.4	13.6	8.2	96.9	128.2
	<i>Mangifera indica</i>	15.7	4.5	93.9	58.1	13.2	8.6	100.2	216.3
	<i>Persea americana</i>	14	9.9	120.2	186.3	18.3	8.3	164.9	177.8
	<i>Senna spp</i>	9.8	4.9	38.3	51.7	5.5	2.9	9.6	15.5
Small woodlots	<i>Eucalyptus spp</i>	8.2	3	20	19.6	7.6	3.9	20.8	35.4
	<i>Euphorbia tirucalli</i>	0	0	0	0	3.1	0.1	1.4	0.1
	<i>Grevillea robusta</i>	9.3	1.3	21.3	9	13.8	7.3	83.7	72.5
	<i>Mangifera indica</i>	0	0	0	0	0.0	0.0	0	0
	<i>Persea americana</i>	0	0	0	0	18.3	5.9	136	107.9
	<i>Senna spp</i>	0	0	0	0	6.0	0.0	7.6	0
Trees on road	<i>Eucalyptus spp</i>	0	0	0	0	0.0	0.0	0	0
	<i>Euphorbia tirucalli</i>	10.7	2.4	34.5	19	0.0	0.0	0	0
	<i>Grevillea robusta</i>	9	4.4	27.3	30.9	21.8	11.7	232.2	248.3
	<i>Mangifera indica</i>	0	0	0	0	0.0	0.0	0	0
	<i>Persea americana</i>	0	0	0	0	0.0	0.0	0	0
	<i>Senna spp</i>	18.1	11.1	189	254	0.0	0.0	0	0
Silvopastoral	<i>Eucalyptus spp</i>	0	0	0	0	13.5	7.5	78.3	96.6
	<i>Euphorbia tirucalli</i>	0	0	0	0	12.2	3.8	49.4	37.4
	<i>Grevillea robusta</i>	0	0	0	0	9.0	3.6	25.2	20
	<i>Mangifera indica</i>	0	0	0	0	0.0	0.0	0	0
	<i>Persea americana</i>	0	0	0	0	0.0	0.0	0	0
	<i>Senna spp</i>	0	0	0	0	0.0	0.0	0	0

DBH - diameter at breast height, AGB - aboveground biomass, Std. dev. - Standard deviation

Comparison of Aboveground Biomass in Different Agroforestry Practices

The Kruskal–Wallis test was conducted to compare pairs of aboveground biomass in different agroforestry practices within both project intervention and no intervention areas. The Kruskal–Wallis pairwise comparisons display the sample average rank of each agroforestry practice (Table 3). The Kruskal–Wallis numerical values represent the mean rank, where higher values indicate a higher average ranking or preference. Scattered trees on farm exhibited the highest mean biomass rank in both project intervention and no intervention areas, with 35.50 and 31.00, respectively (Table 3). Boundary planting with 26.92 is also predominant in project intervention areas, almost comparable to home garden with 25.50 in no intervention areas (Table 3). Silvopastoral practice was missing in project intervention areas (Table 3).

DISCUSSION

Trees and Shrub Species Diversity in Surveyed Agroforestry Systems

As expected, *Eucalyptus spp.* was predominant in no intervention areas (46%), particularly in small woodlots while *Senna spp.* was slightly dominant in project intervention areas (20%). In fact, *Senna spp.* were among the species distributed by the LDCF II project (REMA, 2023). *Eucalyptus* and *senna spp.* are generally managed under coppicing system and are repeatedly harvested for firewood and charcoal production. *Eucalyptus spp.* and *Senna spp.* have high regenerative capacity and can sprout multiple times even at older ages (Orwa *et al.* 2009; Ferraz Filho *et al.*, 2014; Inter aid Malawi, 2017; MINILAF, 2018; Kalema and Hamilton, 2020).

Overall, *Eucalyptus spp.*, *Grevillea robusta*, *Mangifera indica*, *Persea americana*, *Euphorbia tirucalli*, and *Senna spp.* were the most dominant tree species across all study sites, both in project intervention (84%) and no intervention areas (72%). The farmers prefer these species due to their socio-economic values, more specifically, food, firewood, construction materials, etc. While *Eucalyptus* and *Grevillea* are generally grown for timber and fuelwood production among many other uses (Ndayambaje *et al.*, 2014; Mukuralinda *et al.*, 2016), *Euphorbia tirucalli* is effective as a boundary demarcation tree, and *Mangifera indica* and *Persea americana* are well cherished fruit trees in Rwanda with notable importance for nutrition and income for farmers.

Meanwhile, *Combretum molle* and *Markhamia lutea*, which are native species, were slightly more prominent in no-intervention areas. This may suggest that traditional agroforestry systems maintain higher representation of indigenous species, while project

interventions tend to favor introduced or promoted species with clearer short-term economic returns. Similar patterns have been reported in intervention-driven agroforestry landscapes where extension services promote species with predictable growth rates and market value (Franzel *et al.*, 2001).

Trees and Shrub Stocking in Project Intervention and no Intervention Areas

The LDCF II project promoted planting of beneficial tree species to farmers and the environment which led to high agroforestry adoption and hence increased tree density in agricultural landscapes under project intervention areas (REMA, 2023). Indeed, tree and shrub density was four times higher in project intervention areas (172 stems ha⁻¹) than in no-intervention areas (43 stems ha⁻¹), clearly demonstrating the positive effect of project support on tree establishment and retention on farms. This difference reflects improved access to planting materials, technical guidance, and farmer awareness under the project. Several studies have reported that agroforestry adoption in Eastern Rwanda is still low with tree densities ranging from 20 to 167 ha⁻¹ across elevation gradients (Ndayambaje *et al.*, 2014; Mukuralinda *et al.*, 2016; Ruticumugambi *et al.*, 2024).

The highest proportion of inventoried trees and shrubs were small (with a DBH < 10 cm) in both project intervention (69.4%) and no intervention areas (71.4%). The dominance of small DBH classes (< 10 cm) indicates young or frequently managed tree populations, typical of smallholder agroforestry systems where trees are regularly pruned or harvested. Indeed, the prevalence of smaller diameter trees in both zones, reflect the harvesting of young trees in agroforestry systems not only to meet domestic energy needs but also to reduce competition with crops (Bapfakurera *et al.*, 2024). However, the higher proportion of larger trees in no-intervention areas suggests longer-standing trees with less intensive management or delayed harvesting.

Aboveground Biomass Distribution among Agroforestry Practices

Despite smaller average tree sizes, project intervention areas exhibited a substantially higher total biomass (15.33 t ha⁻¹) compared to no-intervention areas (4.51 t ha⁻¹). This contrast is primarily explained by much higher tree density and wider adoption of biomass-efficient practices, rather than individual tree size. This finding underscores the importance of tree density and spatial configuration, rather than individual tree size, in determining biomass outcomes in agroforestry systems (Henry *et al.*, 2011; Kuyah *et al.*, 2012). Indeed, increased tree density is a well-established determinant of aboveground carbon stocks in agroforestry systems (Nair *et al.*, 2009).

Table 3: Kruskal–Wallis test ranks of agroforestry biomass across agroforestry practices

Project intervention areas		No intervention areas	
Agroforestry practice	Mean Biomass Rank	Agroforestry practice	Mean Biomass Rank
Small woodlot	12.67	Trees on the road	13.25
Trees on the road	19.92	Silvopastoral	17.58
Intercropping	23.08	Boundary planting	18.67
Home garden	23.92	Small woodlot	21.92
Boundary planting	26.92	Intercropping	22.58
Scattered trees on farm	35.50	Home garden	25.50
		Scattered trees on farm	31.00

Scattered trees on farm were the dominant practice in intervention areas (42.2%) and contributed the highest biomass in both zones, confirming this practice as the most effective biomass accumulator in smallholder systems. In no-intervention areas, small woodlots dominated (40.5%), yet their biomass contribution remained relatively low, likely due to low stocking density, smaller tree size, or frequent harvesting. Intervention areas showed a more diversified practice portfolio, including higher proportions of home gardens, intercropping, boundary planting, and roadside trees, collectively enhancing overall biomass. Previous studies have similarly shown that dispersed trees contribute disproportionately to landscape-level carbon stocks in agricultural mosaics (Zomer *et al.*, 2016). The absence of silvopastoral systems in intervention areas suggests either project area coverage limitations or land-use constraints that restrict integration of trees and livestock.

Tree Size and Species-level Biomass Patterns and Across Agroforestry Practices

Across practices, trees in no-intervention areas consistently had larger DBH and higher AGB per stem, as illustrated by *Grevillea robusta* in home gardens (181.7 vs 65.1 kg stem⁻¹), and *Persea americana* (185.8 vs 51.7 kg stem⁻¹). This pattern indicates that trees in no-intervention areas are older, whereas intervention sites are characterized by younger stands and active management, including pruning and selective cutting. This finding aligns with agroforestry intensification pathways that favour rapid establishment and early ecosystem service delivery (Nair, 2011).

Despite smaller sizes, intervention areas achieved higher landscape-level biomass, and this was either due to (i) higher tree density, (ii) strategic placement of trees (scattered, boundary, and home gardens), or (iii) use of fast-growing species. The repeated dominance of *Grevillea robusta*, *Mangifera indica*, and *Persea americana* across practices highlights their central role in balancing production and ecological functions, while *Euphorbia tirucalli* remains important for live fencing and boundary stabilization.

The Kruskal–Wallis results confirm significant variation in biomass accumulation among agroforestry practices. Scattered trees on farm ranked highest in both zones (mean rank 35.50 in intervention and 31.00 in no-intervention areas), underscoring their superior contribution to aboveground biomass. Boundary planting ranked relatively high in intervention areas (26.92), suggesting effective use of farm boundaries for biomass accumulation under project guidance. In no-intervention areas, home gardens ranked higher than in intervention areas, likely reflecting older, well-established perennial systems. These results reinforce the view that practice choice is a stronger determinant of biomass accumulation than species identity alone, a conclusion consistent with earlier agroforestry research emphasizing management configuration over species effects (Albrecht and Kandji, 2003).

CONCLUSION

This study demonstrates that targeted agroforestry interventions substantially influence tree stocking, practice configuration, and aboveground biomass accumulation in smallholder farming systems. While species richness was similar between project intervention and no-intervention areas, intervention sites were characterized by higher tree densities, younger diameter classes, and markedly greater aboveground biomass per hectare. These findings indicate that project-supported agroforestry can rapidly enhance biomass and associated ecosystem services, even at early stages of stand development.

Scattered trees on farm consistently emerged as the most biomass-efficient agroforestry practice across both zones, underscoring their central role in multi-functional agroforestry system design. Boundary planting and home gardens further contributed to biomass accumulation in intervention areas, highlighting the importance of spatial tree integration rather than reliance on woodlots alone. Although trees in no-intervention areas exhibited higher biomass per stem, the situation of greater stem density in intervention systems apparently compensated for smaller tree sizes, resulting in higher landscape-level biomass.

From a climate mitigation perspective, the higher aboveground biomass observed in intervention areas suggests strong potential for carbon sequestration and relevance to results-based climate-finance mechanisms. However, sustaining and enhancing this potential will require longer rotation periods, reduced premature harvesting, and improved species diversification, particularly through greater inclusion of native species.

Overall, the results confirm that agroforestry interventions can effectively shift smallholder landscapes toward high-density, actively managed systems that deliver multiple benefits, including biomass production, climate mitigation, and livelihood support. Future agroforestry interventions should prioritize practice diversification, adaptive management, native tree species and long-term monitoring to maximize ecological sustainability and even climate-finance readiness.

ABBREVIATIONS

AGB	Above-ground Biomass
DBH	Diameter at Breast Height
EbA	Ecosystem-based Adaptation
GEF	Global Environment Facility
LDCF	Least Developed Countries Fund
MINILAF	Ministry of Lands and Forestry
REMA	Rwanda Environmental Authority
SDGs	Sustainable Development Goals
spp	Species
TBS	Tree-based System
UNEP	United Nations Environmental Programme

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CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

REFERENCES

- Albrecht A. and Kandji S.T. (2003). Carbon sequestration in tropical agroforestry systems. *Agric. Ecosys. Environ.*, **99**, 15-27. [http://dx.doi.org/10.1016/S0167-8809\(03\)00138-5](http://dx.doi.org/10.1016/S0167-8809(03)00138-5)
- Bapfakurera E.N., Nduwamungu J., Nyberg G. and Kilawe C.J. (2024). Assessment of stocking, productivity, and aboveground biomass of tree species used as fuelwood in Rwanda's agricultural landscapes. *Trees, For. People*, **16**, Article No. 100552. <https://doi.org/10.1016/j.tfp.2024.100552>
- Collier P., Conway G. and Venables T. (2008). Climate change and Africa. *Oxford Rev. Econ. Policy*, **24** (2), 337-353. <https://doi.org/10.1093/oxrep/grn019>
- Dagar J.C., Gupta S.R. and Teketay D. (2020). *Agroforestry for Degraded Landscapes: Recent Advances and Emerging Challenges*, Vol. 1. <https://doi.org/10.1007/978-981-15-4136-0>
- East African Community (2011). East African Community Climate Change Policy (EACCCP)
- FAO and UNEP (2020). The State of the World's Forests 2020. Forests, Biodiversity and People. Food and Agriculture Organization (FAO), Rome, Italy. <https://doi.org/10.4060/ca8642en>
- Ferraz Filho A.C., Scolforo J.R.S. and Mola-Yudego B. (2014). The coppice-with-standards silvicultural system as applied to Eucalyptus plantations - a review. *J. For. Res.*, **25** (2), 237-248. <https://doi.org/10.1007/s11676-014-0455-0>
- Franzel S., Coe R., Cooper P., Place F. and Scherr S. (2001). Assessing the adoption potential of agroforestry practices in sub-Saharan Africa. *Agric. Sys.*, **69** (1-2), 37-62. [https://doi.org/10.1016/S0308-521X\(01\)00017-8](https://doi.org/10.1016/S0308-521X(01)00017-8)
- Gupta G.S. (2019). Land degradation and challenges of food security. *Rev. Europ. Stud.*, **11** (1), Article No. 63. <https://doi.org/10.5539/res.v11n1p63>
- Henry M., Picard N., Trotta C. *et al.* (2011). Estimating tree biomass of sub-Saharan African forests: a review of available allometric equations. *Silva Fennica*, **45** (3B), 477-569
- Inter aid Malawi (2017). Agroforestry practice: Guidelines for pruning *Senna spectabilis*
- Kalema J. and Hamilton A. (2020). Field guide to the forest trees of Uganda: For identification and conservation. In: *Field Guide to the Forest Trees of Uganda: For Identification and Conservation*. <https://doi.org/10.1079/9781789245271.0000>
- Kayonza (2018). Kayonza District Development Strategy (DDS) 2017-2024. <https://Knowledge-Uclga.Org/IMG/Pdf/Kayonzadistrict.Pdf>
- Kuyah S., Dietz J., Muthuri C. *et al.* (2012). Allometric equations for estimating biomass in agricultural landscapes: II. Belowground biomass. *Agric. Ecosys. Environ.*, **158**, 225-234. <https://doi.org/10.1016/j.agee.2012.05.010>
- Li C., Yang M., Li Z. and Wang B. (2021). How will Rwandan land use/land cover change under high population pressure and changing climate? *Appl. Sci.*, **11** (12), Article No. 5376. <https://doi.org/10.3390/app11125376>
- Ministry of Lands and Forestry (2018). Rwanda National Forestry Policy 2018. Ministry of Lands and Forestry (MINILAF), Rwanda
- Muhoza R.N., Imaniraho D., Nshimiyimana A., Nkunzabo E., Ntezimana N.J. and Batera N. (2023). The effect of teaching aids on students' performance in Biology subject in O'level secondary schools in Kayonza District. *J. Res. Innov. Implications Edu.*, **7**, 124-133. <https://doi.org/10.59765/uski1839>
- Mukuralinda A., Ndayambaje J.D., Iiyama M. *et al.* (2016). Taking to Scale Tree-Based Systems in Rwanda to Enhance Food Security, Restore Degraded Land, Improve Resilience to Climate Change and Sequester Carbon. The Programme on Forests (PROFOR), Washington D.C. https://www.profor.info/sites/default/files/TakingToScaleRwanda_low.pdf
- Nair P.K.R., Nair V.D., Kumar B.M. and Haile S.G. (2009). Soil carbon sequestration in tropical agroforestry systems: a feasibility appraisal. *Environ. Sci. Policy*, **12** (8), 1099-1111. <https://doi.org/10.1016/j.envsci.2009.01.010>
- Nair P.K.R. (2011). Agroforestry systems and environmental quality: Introduction. *J. Environ. Qual.*, **40** (3), 784-790. <https://doi.org/10.2134/jeq2011.0076>
- Ndayambaje J.D., Mugiraneza T. and Mohren G.M.J. (2014). Woody biomass on farms and in the landscapes of Rwanda. *Agrofor. Sys.*, **88** (1), 101-124. <https://doi.org/10.1007/s10457-013-9659-0>
- Orwa C, Mutua A., Kindt R., Jamnadass R. and Simons A.J. (2009). Agroforestry database: A tree reference and selection guide, version 4.0. <http://apps.worldagroforestry.org/treedb2/>
- Regreening Africa (2023). Outcome Story for Rwanda: Establishment of Agroforestry Task Force to Implement National Agroforestry Strategy. World Agroforestry, Nairobi, Kenya
- REMA (2021). Rwanda State of Environment and Outlook Report 2021. Rwanda Environment Management Authority (REMA), Kigali
- REMA (2023). Compiled Final Evaluation Report for LDCF II Project. Rwanda Environment Management Authority (REMA), Kigali
- Ruticumugambi J.A., Kaplin B., Blondeel H. *et al.* (2024). Diversity and composition of agroforestry species in two agro-ecological zones of Rwanda. *Agrofor. Sys.*, **98** (6), 1421-1443. <https://doi.org/10.1007/s10457-024-01011-9>
- UNDP (2023). Ecosystem Restoration: Country Dossier - South Africa. United Nations Development Programme (UNDP), New York
- UNECA (2017). Assessing the Impact of Climate Change on Agricultural Production, Trade and Food Security in the East African Community. United Nations Economic Commission for Africa (UNECA), African Climate Policy Centre (ACPC). Final Report, July 2017
- USAID (2018). Improving Ecosystem Management to Strengthen Resilience to Extreme Weather in the Philippines: An Ecosystem-based Adaptation Approach. United States Agency for International Development (USAID), Washington, DC 20523. <https://www.ri.org/content/uploads/2019/08/Improving-Ecosystem-Management-to-Strengthen-Resilience-to-Extreme-Weather-in-the-Philippines.pdf>
- Wheeler T. and Von Braun J. (2013). Climate change impacts on global food security. *Science*, **341** (6145), 508-513. <https://doi.org/10.1126/science.1239402>
- Zomer R., Neufeldt H., Xu J. *et al.* (2016). Global tree cover and biomass carbon on agricultural land: The contribution of agroforestry to global and national carbon budgets. *Scientific Reports*, **6**, Article No. 29987. <https://doi.org/10.1038/srep29987>