Tree occurrence in agricultural landscapes of peri-urban Kigali in semi-arid context of Rwanda

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Abstract

In tropical Africa, a wide range of agroforestry practices exist, resulting in various configurations of trees in the landscape, with an unknown impact on ecosystem services. We evaluated tree occurrence, structure, and composition in agroforestry systems within four contrasting landscapes representing different levels of tree cover in peri-urban Kigali and in the eastern province of Rwanda. We used a stratified random sampling procedure, based on soil depth and slope, to allocate 60 plots of 0.26 ha in each of the four landscapes. We conducted an extensive field inventory to provide deeper insight into the dendrometric characteristics of woody vegetation and compare landscapes. We counted all woody plants with ≥ 4 cm diameter at breast height (DBH). Over 70% of the individual trees were exotic tree species across the four agricultural landscapes. The three most common and dominant tree species across the landscapes were *Grevillea robusta*, a tree used mainly for timber which represents 42.7% of all individuals encountered, followed by *Mangifera indica (*12.34%) mainly used for fruit production, and *Euphorbia turcalii* (11.04%) mainly used for hedgerows. Most of the agroforestry trees encountered were small, scattered individuals, with almost 80% < 15 cm DBH bordering the farmlands and cut before reaching bigger sizes. The occurrence of trees varied considerably within and between landscapes, suggesting the effect of agroecological systems. Here, future studies may potentially address this link more explicitly. We showed that it is important to consider native tree species in landscape restoration initiatives given a high adoption rate of exotics.

Introduction

Agricultural landscape occupies the biggest land use sector both globally and across country income groups (Taylor & Rising, 2021). Urbanization growth coupled with the shift in the evolution of global land use to agricultural intensification have implications for food security, carbon emissions, biodiversity loss and associated loss of ecosystem services at local and landscape scales (Anwar et al., 2023; Petsch et al., 2021; Roy et al., 2022). Over the past 300 years, agricultural expansion and timber extraction have caused a loss of approximately 11 million km^2 of forest worldwide (Foley et al., 2005). This trend tends to make agricultural ecosystems less resilient and more vulnerable to global environmental changes (Foley et al., 2005; Tscharntke et al., 2011). Agricultural landscapes have been transformed over time due to growing demands of natural resources, which affects the spatial distribution patterns, structure and composition of the agricultural land mosaic (Sallustio et al., 2018). In this context, trees on farms ("agroforestry") is often depicted as a high potential solution for the increasing demand for food security and livelihoods of small-holder farmers, resilient to the multiple stressors that agricultural systems are currently facing in the global South (Berkum, 2023; Borelli & Conigliaro, 2014; Iiyama et al., 2018a; Waldron et al., 2017).

Because trees interact with each other and the level of their interactions depend on individual tree architecture and structural characteristics including morphological measures such as crown dimension (e.g., crown diameter, crown projected area) and stem attributes (e.g., diameter at breast height (DBH), height, height of crown base), it is important to investigate individual trees to understand the ecosystem functioning of any agroforestry landscape (Saarinen et al., 2021). Furthermore, the spatial configuration and structure of the individual trees within a landscape influence the landscape ecosystem functions (Van Den Berge, 2021; Delavaux et al., 2023; Lausch et al., 2015). For instance, trees on farms represent key elements (Chirwa & Mala, 2016). Trees outside of forests (ToF) contribute to biodiversity by increasing connectivity for managing biodiversity out of protected areas in fragmented landscapes (Amichev et al., 2020; Atangana et al., 2014; Prevedello et al., 2018). Thus, trees on farms in a human modified landscape are frequently considered as "keystone structures" due to their disproportionate contribution in facilitating movement across the landscape (Silva et al., 2020; Yadessa et al., 2009). The spatial configuration of the woody elements in agricultural landscapes influences many ecological processes such as the distribution and movement of organisms, spread of disturbances (e.g., pest and diseases), and energy flow. Furthermore, trees on farms improve microclimate in adjacent fields (Sanchez & McCollin, 2015), enrich the soil with organic material (Van Den Berge, 2021; Cardinael et al., 2017; Follain et al., 2007; Paul, 2018) and potentially contribute to crop yields and more resilient production systems (St.Clair & Lynch, 2010; Palma et al., 2007; Rivest et al., 2013).

Trees on farms provide multiple benefits. For instance, a study by Yadessa et al. (2009) showed that native trees retained in agricultural landscapes promote multiple ecosystem services as patches or islands of high pH and nutrient accumulation. In addition, trees on farms have potential to make an important contribution to climate change mitigation, as they constitute a carbon sink and source of woody biomass for applications in bio-based economies (Mugabowindekwe et al., 2022; Rahayu et al., 2019; Verchot et al., 2007). Trees on farms are considered an effective way to contribute to food security, and socio-ecological resilience in agricultural landscapes (Bolívar-Santamaría & Reu, 2021; Mithöfer et al., 2017; Sharma et al., 2019). However, the multiple ecosystem goods and services delivered by agroforestry landscapes depends not only on spatial configuration and structure of trees in the landscapes, but also on the size and number of individual trees (Numbisi et al., 2021).

The retention of woody perennials within farming systems has been a traditional land use approach developed by subsistence farmers throughout the tropics (Chirwa & Mala, 2016; Kay et al., 2018). In sub-Sahara Africa, trees on farms account for 17% of the global gross annual income of those households and trees were introduced into farms by colonials or were selectively retained after land use change and farmers prefer to manage a mix of native and exotic trees species on farms depending on a range of ecosystem services provided by those agroforestry trees (Kuyah et al., 2016; Yadessa et al., 2009; Zinngrebe et al., 2020). In Rwanda, agroforestry has been part of agricultural practices for hundreds of years (Ndayambaje & Mohren, 2011; Papy, 1975). An important characteristic of traditional agroforestry (AF) in Rwanda is the retention and management of native tree species (Fig. 1a, f) on farms such as *Markhamia lutea*, *Ficus spp., Vernonia amygdalina*, *Iboza riparia*, and *Erythrina abyssinica* (Iiyama et al., 2018b). Often, the choice and adoption of agroforestry trees in the farmlands of Rwanda was driven by multipurpose uses of the tree, especially fuel wood, soil fertility improvement, water runoff control, fruits to supplement the diet, livestock fodder, and cultural services, rather than solely driven by biodiversity conservation (Iiyama et al., 2017; Ndayambaje & Mohren, 2011). Hence, in Rwanda there is a variety of agroforestry practices, with a variety of tree species and configurations (Fig. 1).

While differences in woody species composition, spatial configuration and tree structural attributes among agricultural landscapes may be expected, we selected four landscapes as a model to understand how agroforestry works and contributes to the landscape functioning in peri-urban and east province of Rwanda. Here, we compared four contrasting agricultural landscapes to investigate whether tree structure and species composition differ from one landscape to another and reasons for variations. The objectives of the study were to i) describe the on-farm tree species composition and their spatial configuration ii) examine structural properties and the size class distributions of agroforestry trees and compare landscapes. This paper presents ground inventory-based information on tree occurrence in various agroforestry practices and serves as a baseline observation of woody species composition in the agricultural landscape of the study region.

Methods

2.1 Study sites

Our study was conducted in four tropical agricultural landscapes located in Central East Africa south of the Equator at 1°56'38"S and 30°3'34"E along a gradient of landscape variability in the peri urban Kigali and in eastern province of Rwanda (Fig. 2). Essentially, more than 60% of Kigali, the capital city of Rwanda is still rural where agriculture dominates livelihood activities while the eastern province of Rwanda is considered to be the low altitude region with altitude less than 1500 m and rainfall less than 1000 mm (Papy, 1975). The study region comprised by two dominant agro-ecological zones (A) Eastern Savana and (B) Eastern plateau described by altitudes, rainfall and soil characteristics (Delepierre, 1982). Two landscapes in each agro ecological zone i.e. Gikomero (peri urban Kigali, Gasabo district), Mukama (Nyagatare district) landscapes in Eastern plateau and Karama, Nyamugari landscapes in Eastern Savana were sampled. In the four landscapes, agriculture occupies the main activity of most people and the largest proportion of land in the region is used for agriculture intensification. In the study region, the conversion of the pasture land (i.e. Umutara) to agricultural land in the last two decades has resulted in degraded, exhausted and unproductive soils which make the region highly vulnerable to climate change.

2.2 Landscape selection and plot sampling

With the intention of covering the agroecological zones of the study area, four contrasting agroforestry landscapes representing different levels of tree cover, referred to as “adoption rate” in this study, were selected. The land use pattern in Rwanda is characterized by different land use classes from settlements to intensive agricultural lands (Supplementary information Table SI 1). We determined the potential hillside agroforestry area on hillside agricultural land in each of the four landscapes based on land use land cover classification generated via combining different geographical layers available in the country, plus a photo interpretation of a series of high-resolution satellite images from Worldview (NISR, 2019). We stratified the landscapes into six strata based on the landscape suitability (Verdoodt & Van Ranst, 2006) and only soil depth and slope gradient were used to stratify landscapes. We used a grid of 5x5km, overlaid it with land cover map and selected four landscapes. We used a stratified random sampling procedure, based on soil depth and slope, to allocate 60 0.26 ha plots in each landscape, making a total of 240 sampling plots. For the slope variable, three categories in percentage: 1. 0–10%; 2. >10–20%; and 3. >20% were used. Soil depths were simplified and only shallow < 0.5 and deeper > 0.5 m soils were used as well.

2.3 Woody vegetation inventory

Woody vegetation data for this study were collected in plots of 0.26 ha in size. The inventory resulted in a dataset of 221 plots, with a total of 1467 trees sampled. For a few of the randomly selected plot locations, we did not do an inventory to avoid the variability among plots of different agro ecological zones (Papy, 1975; Verdoodt & Van Ranst, 2006). Thus, the final number of surveyed plots was less than the initial sample size. We measured all woody plants with ≥ 4 cm diameter at breast height (dbh) following standard forest inventory methods; a threshold was set because measuring all individual small trees would be very time-consuming. In the field, basic plot characteristics that could help to explain the variability patterns between landscapes were observed.

Plot-level information recorded included species composition of the plot and the spatial configuration of the trees within a plot (e. g scattered individual trees, trees in line and trees in block). Individual tree structural properties, or ‘structural variables’ recorded included the diameter at breast height (DBH), height and crown diameter (e.g average crown diameter for a long axis crown diameter and crown perpendicular axis diameter) in each sample plot. Stem diameter was measured at 1.30 m height for every tree having DBH > 4cm in the sample plot using a vernier caliper and a diameter tape in centimeters. For multi-stemmed trees all the stems were counted and dbh were measured for the median tree. Tree height was determined using an Haga Altimeter. In the context of this study, a woody plant was defined as a tree and shrub that is wild/retained or was planted in the farmland (Table 1).

3 Statistical Analysis

The percentage of potential land for agroforestry within each landscape was determined using ArcGIS. All statistical analysis was performed using R software (R Core Team 2022). Using the dataset of 1467 trees, the frequency (as a measure of abundance) for each species in the four landscapes was computed as the percentage of individual species to the total number of species encountered. We used Non-metric multidimensional scale (NMDS) with Bray–Curtis distance to identify differences and similarities between the four landscapes. We calculated vegetation structure using plot-level means of six structural measures (stem density per ha, basal area per ha and crown projected area per ha, diameter at breast height, and crown size) for the entire dataset and for each landscape and by tree configuration for each landscape, and we compared landscapes using Kruskal-Wallis test. We performed pairwise comparison using the Wilcoxon test. A Bonferonni correction was used as a method for multiple testing adjustment. In addition, we calculated species richness separately using the vegan package in R to compare ecological significance of woody species within spatial configuration and across landscapes. Lastly, the overall population structure was analyzed by construction of size class distributions of all the individuals encountered in subjectively assigned diameter growth classes. The four diameter growth classes were recognized arbitrarily (*1 = Very small: ≤ 15 DBH); 2 = Small: DBH 16 to 27; 3 = Medium: DBH 28 to 39; 4 = Large: DBH ≥ 40*).

Results

4.1 Tree species composition and distribution across strata

We sampled a total of 1467 on-farm woody agroforestry trees across the two agroecological zones corresponding to 30 woody species across the four agricultural landscapes, representing 19 families with different life forms including 18 and 12 species described as tree and shrubs respectively. In all woody species inventoried 78% were exotic. In the four agricultural landscapes, the most frequent species was *Grevillea robusta* (42.74%), followed by *Mangifera indica* (12.34%) and *Euphorbia turcalii* (11.04%).

Table 1

Estimates of the fractional species composition per landscape. Local names: Kinyarwanda name; Life form (LF): T/S - Tree or shrub; Nature of the establishment: W-Wild, P- planted; and origin: Native or Exotic (N/E) of trees species detected in the four agricultural landscapes of the peri urban Kigali and East province of Rwanda. Frequency (%) as a measure of species abundance were used to provide the proportion of encountered individuals per landscape. The woody species were ranked in descending order of their overall abundance across landscapes.

							Landscape				Overall
S/N	**Tree_species**	**Local name**	**Family**	**LF**	**W/P**	**N/E**	**Karama**	**Nyamugari**	**Gikomero**	**Mukama**	
1	*Grevillea robusta*	Gerevileya	Proteaceae	T	P	E	17.86	8.99	46.22	75.51	**42.74**
2	*Mangifera indica*	Umwembe	Anacardiaceae	T	P	E	10.71	27.34	11.07	4.55	**12.34**
4	*Euphorbia tirucalii*	Umuyenzi	Euphorbiaceae	S	P	N	47.32	11.15	1.05	4.80	**11.04**
5	*Persea americana*	Avocado	Lauraceae	T	P	E	8.04	4.68	13.88	5.56	**9.00**
6	*Carica papaya*	Ipapayi	Caricaceae	S	P	E	0.45	18.71	3.16	1.77	**5.32**
7	*Eucalyptus spp*	Inturusu	Myrtaceae	T	P	E	5.36	8.99	1.41	3.54	**4.02**
8	*Cedrela cerrata*	Cedrela	Meliaceae	S	P	E	-	-	2.46	1.52	**1.36**
9	*Ricinus communis*	Ikibonobono	Euphorbiaceae	S	W	N	-	0.72	2.99	-	**1.30**
10	*Senna spectabilis*	Senna	Fabaceae	T	P	E	2.68	2.16	0.70	0.51	**1.23**
11	*Vernonia amygdalina*	Umubirizi	Asteraceae	S	P	N	1.79	2.52	0.18	-	**0.82**
12	*Jacaranda mimosafolia*	Jacaranda	Bignoniaceae	T	P	E	-	-	1.76	-	**0.68**
13	*Citrus lemon*	Indimu	Rutaceae	S	P	E	-	1.44	0.88	-	**0.61**
14	*Combretum molle*	Umurama	Combretaceae	T	W	N	2.23	-	-	0.25	**0.41**
15	*Leucena leucocephola*	Leucena	Fabaceae	S	P	E	-	-	0.70	0.25	**0.34**
16	*Scenacio manii*	Umutagara	Asteraceae	S	W	N	-	-	0.35	0.76	**0.34**
17	*Dombeya gotsenii*	umukore	Sterculiaceae	T	W	N	-	0.72	-	0.51	**0.27**
18	*Macademia ternifolia*	Macademia	Proteaceae	T	P	E	-	-	0.70	-	**0.27**
19	*Ziziphus abyssinica*	Umukugutu	Rhamnaceae	T	W	N	0.45	1.08	-	-	**0.27**
20	*Kigelia africana*	umuvungavungo	Bignoniaceae	T	W	N	0.89	-	-	-	**0.14**
21	*Teclea nibilis*	Umuzo	Rutaceae	S	W	N	-	0.72	-	-	**0.14**
22	*Acacia hockii*	Umugenge	Mimosaceae	T	W	N	-	0.72	-	-	**0.14**
23	*Albizia petersiana*	Umumeyu	Mimosaceae	T	W	N	-	0.72	-	-	**0.14**
24	*Erytrina abyssinica*	umuko	Fabaceae	T	P	N	-	-	0.18	-	**0.07**
25	*Zanthoxylum usambarense*	Intare y'irungu	Salvadoraceae	T	W	N	0.45	-	-	-	**0.07**
26	*Markhamia obtusifolia*	Umukundambazu	Bignoniaceae	T	W	N	0.45	-	-	-	**0.07**

							Landscape				Overall
S/N	Tree_species	Local name	Family	LF	W/P	N/E	Karama	Nyamugari	Gikomero	Mukama	
27	*Olea africana*	Umunzenze	Oleaceae	T	W	N	-	0.36	-	-	**0.07**
28	*Osyris lanceolata*	Umushishi	Santalaceae	S	W	N	0.45	-	-	-	**0.07**
29	*Cassia didymobotrya*	Umucyuro	Caesalpiniaceae	S	W	N	-	0.36	-	-	**0.07**
30	*Psidium guayava*	Ipera	Myrtaceae	T	P	E	-	-	0.18	-	**0.07**
							100.00	100.00	100.00	100.00	**100.00**

The percentage area potentially for agroforestry among landscapes fluctuated within and across strata (Supplementary information Table SI 2). The highest area was found in Karama landscape (38.0%) followed by Nyamugari (26.09%), Mukama (19.9%) and Gikomero landscape (15.2%). The highest woody agroforestry trees (432 tree individuals) across landscapes were found in stratum two while the lowest number of individuals (118 and 127 tree individuals) were found in stratum five and six respectively. We visualized the multidimensionality in species composition and occurrence in strata using NDMS. We found that tree species composition differed between landscapes. Figure 3 shows the Bray-Curtis-based nonmetric multidimensional scaling ordination (NMDS) for species composition for all landscapes. The direction and length of the arrow indicates the strength of strata with their association with composition of tree species in the four agricultural landscapes.

4.2 Tree densities and spatial arrangements

We found the highest number of trees scattered in the farmlands, with individual trees unevenly distributed across the four agricultural landscapes. The average tree density of 54.6 trees/ha (St.dev = 5.5) across the four agricultural landscapes. The highest individuals per ha were found in Mukama (63.1 trees/ha) and in Gikomero (59.9 trees/ha) landscapes. However, we found stem density per ha (46.9 trees/ha) in Nyamugari and Karama landscape (35.9 trees/ha) both below the overall average tree density of the four studied landscapes. Overall, most of the trees were spatially scattered on the farmland across landscapes and were found to be very small with an average height of 6.6 cm, stem diameter at breast height of 10.8 cm corresponding to an average basal area of 0.62 m^2 /ha and crown diameter of 2.8m which corresponds to an average crown projected area of 34 m^2 /ha. Scattered individuals (more than five meters from any other tree) were the most frequently encountered configuration in the farmlands in different size classes (Fig. 5). The spatial configuration in the fields in each of the four agricultural landscapes indicates 61.6 trees/ha in line, 53.8 trees/ha; 48.2 trees/ha scattered individual trees and trees in blocs respectively (Table 2 and Supplementary information Table SI 4).

Overall, the results indicate that almost all variables of interest differed between landscapes. Figure 4. illustrate the differences of the four landscapes on the aspects of structural attributes including stem density, basal area, crown projected area, height, dhb and crawn diameter. Landscapes sharing the same agroecological zone tend to behave similarly. For instance, we found no significant difference in individuals per ha between Gikomero and Mukama landscapes (Fig. 4, A) and no significance difference was found in individuals per ha between Nyamugari and Karama landscapes. Similar patterns were observed even for other variables across landscapes (Fig. 4 and Supplementary information Table SI 3). Overall, the results show no significance difference between landscapes by native woody species encountered across landscapes; stem density per ha (W = 210940, p-value = 0.0001), basal area ha (W = 222273, p-value = 0.001) and crown projected area (W = 254053, p-value < 0.0001) (Supplement information Fig. 1).

4.3 Tree structure (DBH, Height and Crown Size)

The results of the tree structural characteristics indicate the high occurrence of small woody agroforestry trees at different stages of development, common across all sampled landscapes (Figs. 4 and 5). We found a crown diameter ranging between 0.2–5.2 m, with average crown diameter of 2.8 m across landscapes. The average tree height in the four landscapes was 6.8 m with a corresponding average DBH of 10.8 cm (Table 3).

Table 2

Dendrometric characteristics of inventoried trees per species in all four agricultural landscapes. Frequency (%) as a measure of species abundance was used to provide the proportion of individuals for the eleven most dominant tree species. Trees species with a total frequency less than 1% (Appendix Table 1*) were combined in one group and called 'others. The number of individual trees and density in each is tree configuration type is indicated: trees in line (L), trees in block (B), scattered trees in the farmland (S). N: total number of trees encountered, D: average diameter at breast height (1.3m above the ground), cr: average crown diameter and h: average height. The mean values data of the individual species are presented.*

Species composition	Vegetation status	Overall Species Frequency (%)	N			D (cm)	Cr (m)	H (m)
			L (n = 464; ~ 61.6 trees/ha)	B (n = 421 ; ~ 48.2 trees/ha)	S (n = 582 ~ 53.8 trees/ha)	Mean	Mean	Mean
Carica papaya	Exotic	5.32	1(0.1)	17(1.2)	60(4.1)	10.2 ± 0.42	1.6 ± 0.09	3.7 ± 0.2
Cedrela cerrata	Exotic	1.36	3 (0.2)	2(0.1)	15(1.0)	13.4 ± 1.12	2.8 ± 0.19	8.6 ± 0.63
Eucalyptus spp	Exotic	4.02	8(0.5)	41(2.8)	10(0.7)	8.8 ± 0.55	2.3 ± 0.15	9.4 ± 0.57
Euphorbia tirucalii	Native	11.04	22(1.5)	108(7.4)	32(2.2)	9.1 ± 0.41	1.7 ± 0.11	4.5 ± 1.1
Ficus spp	Native	1.09	1(0.1)	0(0)	15(1.0)	22.9 ± 4.21	4.7 ± 0.76	7.1 ± 0.81
Grevillea robusta	Exotic	42.74	395(26.9)	6(0.4)	226(15.4)	10.1 ± 0.23	3.0 ± 0.05	7.9 ± 0.13
Mangifera indica	Exotic	12.34	8(0.5)	130(8.9)	43(2.9)	12.4 ± 0.56	2.9 ± 0.16	5.1 ± 0.12
Markhamia spp	Native	5.45	7(0.5)	23(1.6)	50(3.4)	8.8 ± 0.47	2.3 ± 0.15	8.2 ± 0.48
Persea americana	Exotic	9	13(0.9)	60(4.1)	59(4.0)	15.6 ± 0.71	4.5 ± 0.21	7.5 ± 0.23
Ricinus comminus	Native	1.3	1(0.1)	0(0)	18(1.2)	6.6 ± 0.48	1.3 ± 0.25	5.6 ± 0.31
Senna spectabilis	Exotic	1.23	2(0.1)	7(0.5)	9(0.6)	6.7 ± 0.72	2.4 ± 0.41	5.7 ± 0.27
Other species	Both	5.11	3(0.2)	27(1.8)	45(3.1)	11.5 ± 1.16	2.8 ± 0.24	6.2 ± 0.28

4.4 Tree counts and size class distribution

As DBH is linked with tree growth rate and age, we grouped woody agroforestry trees into four diameter classes. The size classes distribution of the tree individuals showed right-skewed distribution, demonstrating the trees are disappearing before reaching the bigger size (Fig. 5). The results show the growth and utilization of individual trees at different tree dimensions. Across all four landscapes, more than 80% of the trees were < 15 cm DBH and planted in rows or bordering the farmlands. Across all landscapes, the number of individual trees decreased as the tree size (DBH) increased.

The DBH class distribution of trees on farms differs within and across landscapes (Fig. 5). The results indicate a prevalence of *Grevillea robusta* in almost all classes, but small individuals of G*revillea robusta* were more frequent in Gikomero landscape (peri-urban Kigali) and Mukama (Nyagatare district) while in Karama landscape (Bugesera district), *Euphorbia turcallii* was the most dominant wood species while *Mangifera indica* followed by *Carica papaya* were the most predominant species in Nyamugari landscape (Kirehe district). *Mangifera indica, Ficus spp* and *Persea americana* were the most dominant woody species reaching a large size of *≥ 40cm dbh.*

Discussion

The occurrence of trees on farms influences functions at field as well as at landscape scale. Our study provided a quantitative characterization of the tree occurrence and contrasts among the agricultural landscapes of peri urban Kigali and east drylands of Rwanda. To our knowledge, it is the first study to characterize the agroforestry systems from tree structural attributes and spatial configuration perspective in the study area.

5.1 Landscape structure and tree species composition in the four agricultural landscapes

The ecosystem services provided at landscape scale depend on tree structure and composition. In return, the landscape structure may influence the species composition. The woody species composition identified in the four landscapes differed between landscapes and across strata. The observed low woody species composition in both Karama and Nyamugari landscapes is unexpected given their high percentage area potentially for agroforestry. The low number of agroforestry tree cover could be attributed to inaccessibility to tree genetic resource materials that resist to global environmental change (e.g. pests and diseases), poor matching species with sites, historical deforestation and land use. Furthermore, Verdoodt & Van Ranst (2021) reported that the most important edaphic limitations to crop production in Rwanda are the slope gradient, soil depth and sum of exchangeable basic cations (nutrients) and that where climatic conditions are optimal or near optimal, these soil properties will determine the spatial distribution of the final suitability. Hence, the variation in woody agroforestry trees within and across landscapes of the study region might be correlated with the difference in agroecological zones which is explained by the altitude and soil characteristics (Delepierre, 1982). Here, we argue that the agroecological zones in the study region influence the distribution of woody vegetations.

In the study region, indigenous tree species occurred in small numbers in the four agricultural landscapes. The dominance of exotic tree species was evident in all four landscapes. In all landscapes, exotic trees species represented ~ 70% of the total number of trees recorded. In the entire study region, the three common and dominant tree species planted were *Grevillea robusta*, a tree species used mainly for timber and preferred for their fast growth that can enable farmers to get various benefits within a short period of time (Pedercini & Dawson, 2022) followed by *Mangifera indica* mainly used for fruit production for food and *Euphorbia turcalii* mainly used as hedgerow and farm plot delineation.

We found a considerable amount of multipurpose tree species, widely integrated with perennial crops, e.g *Musa sp.* and *Manihot esculenta* among others but also with seasonal agricultural crops. Our results concur with several other findings which state that the trees on farms provide multiple benefits to the farmers and their retention/planting depends broadly on strong sense of farmers ownership and responsibility compared to landscape structure and to land use intensity (Fikir et al., 2018; Ndayambaje et al., 2012).

Because the retention of trees on farms or decisions to remove trees, is determined by the farmer perceptions including tree interactions with other crops (Ndayambaje et al., 2012), we argue that native trees like *Zanthoxylum usambarense*, *Olea africana* and *Osyris lanceolate* are mostly retained in the study area because of their use as source of medicine for traditional healers. On the other hand, some exotic trees are being grown on farms for timber production, like *Grevillea robusta*, *Cedrela cerrata* and *Eucalyptus spp*, while other exotic tree species are planted mainly for production and provision services including household consumption of fruits (e.g *Persia americana, Mangifera indica, Psidium guajava, Citrus lemon, Macademia ternifolia*) and as a source of income. We found that exotic woody species like *Euphorbia tirucalii* were used for fencing and farm delimitation. In addition, large solitary native trees like *Albizia petersiana* and *Erytrina abyssinica* were retained for hanging traditional beehives, for providing shelter, and for soil fertility improvement.

5.2 Tree densities and spatial arrangements

Our findings on the average tree density (number of individuals per ha) indicated a substantial agroforestry adoption in peri urban Kigali (Gikomero landscapes) and Mukama landscapes, despite the presence of steep terrain (Fig. 2). Although our study did not aim at identifying different landscape structure variables that influence woody species composition in agricultural landscapes, we found that slope together with soil depth in the study region, explain the variability of tree species distribution. Here, we showed that the on-farm woody agroforestry trees may not necessary depend on slope gradient neither by soil depth in the four agricultural landscapes of the study region. However, the high forest land cover in Gikomero and Mukama landscapes could be one of the reasons behind the high woody agroforestry trees, and we indicate that tree resources are within easy reach of people in eatern plateau compared to the eastern savanna (the two agricultural landscapes of Kirehe and Bugesera district).

Tree density in tropical agricultural landscapes vary enormously and such variability is explained by the different methodological approaches, size thresholds and sampled trees, local condition and management (Korol et al., 2021). The structural complexity of individual trees, for instance, the distributional features of tree individuals in a given space at a given time could also contribute to the differences in tree species composition and density and hence influence the landscape functions (Korol et al., 2021; Saarinen et al., 2021). The average tree density observed in our study was 54.6 trees/ha (terrestrial sampling), which is a bit less compared in the study by (Mugabowindekwe et al., 2022) in which 79.6 trees per ha were found in farmlands in Rwanda by using remote sensing. However, in our study the smallest trees that were considered was of ≥ 4cm dbh. Therefore, it is possible that the differences in tree density might be attributed to the fact that (Mugabowindekwe et al., 2022) included trees with less threshold than in our study.

Overall, the results confirm that the four agricultural landscape were different, suggesting the effect of agroecological systems, with low density of native tree species likely related to the conversion of pasture land to agricultural land in the last two decades. We suggest that the overall low tree density in the study area is caused by the early harvesting of trees due to the overall scarcity of trees and woody plants in the landscape and the high demand for wood resources, as well as anticipated competition between fully grown trees and crops. In addition, the studied landscapes may still be at an early stage of agroforestry establishment due to the fairly recent tree planting movement across the country.

5.3 Individual tree structural attributes and their size class distribution

Overall, this study shows that in the four landscapes, the number of individual trees decreases as tree size increases. The dbh size class distribution of the woody agroforestry trees indicate the impact of exploiting tree resources in the study region given the prevalence of smaller trees disappearing before they reach to mature size. The results showed not only the degree to which the four agricultural landscapes are being utilized, but also gives an indication of the local community dependency on tree resources for different purposes. In the study area, tree resources are scarce, and the prevalence of *Grevillea robusta* may have been chosen by most of the farmers because of its fast grow ability and can produce timber, firewood as well as sticks for climbing beans (Cyamweshi et al., 2023). The occurrence of a large number of exotic tree species in the landscape study sites could be explained by the fact that in the Eastern province of Rwanda, which is considered as a semi-arid region, native trees were cut down for agricultural production and replaced with fast growing exotics. Here, we suggested that promoting native tree species in agricultural landscapes can boost landscape sustainability and hence increase production (Gemechu et al., 2021). In this study, most of the trees in the large classes were native tree species which might have been retained for their supportive and cultural services (Cyamweshi et al., 2023). Although the ecosystem services perceptions may determine the adoption rate of trees on farms, the results on the individual structural properties indicate that choice of species to be planted or retained might depend on its structural attributes apart from socio ecological factors. Further, the differences in tree occurrence may further be influenced by global environmental change and types of disturbances including droughts and pest and diseases among others.

Conclusion

This study provides baseline data on the woody species composition in the agricultural landscape of peri urban Kigali and east drylands of Rwanda. We found that tree species composition differed between the landscapes with a prevalence of exotic species in all landscapes. *Grevillea robusta* was found to be the most abundant tree species mainly for its multipurpose use including timber provision. Scattered individuals represented a large number of trees counts in the farmlands. We found that most of the agroforestry trees encountered were small scattered individuals; almost 80% of the trees were smaller than 15 cm DBH bordering the farmlands and were cut before reaching bigger sizes. Additionally, our study sheds light on the adoption of agroforestry practices in the region, including tree species selection, planting configuration, uses of those species and the balance between resource needs and resource access or availability. We showed that it is important to consider the native tree species in landscape restoration initiatives given a high adoption rate of exotics. The dominance of exotic trees in the farmlands over native species suggests more work needs to be done to understand the low adoption or use of native trees in farmlands. We highlight several areas for future research, such as diversifying agroforestry tree species, promoting sustainable tree planting on farms from an ecological perspective, including the enhancement of biological diversity across different taxa. Additionally, we emphasized the importance of sustainable livelihoods, climate change adaptation, and food security in relation to these endeavors. Lastly, we suggest that including other habitat types in future studies will further improve our understanding of historical land use and tree legacy in the study region.

Declarations

Data availability statement

The raw data supporting the discussion and conclusion of this article will be made available by the authors, upon reasonable request.

Authors Contributions

Kris Verheyen, Frieke Vancoillie, Hans Verbeeck and Beth A. Kaplin supervised and provided guidance throughout all aspects of the research. Jean Aimé Ruticumugambi, designed the study, collected data during the field campaign. Jean Aimé Ruticumugambi and Haben Blondeel performed the processing and data analysis. All the authors contributed to the interpretation of the results and to the text of the manuscript.

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Conflict of interests

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Figures

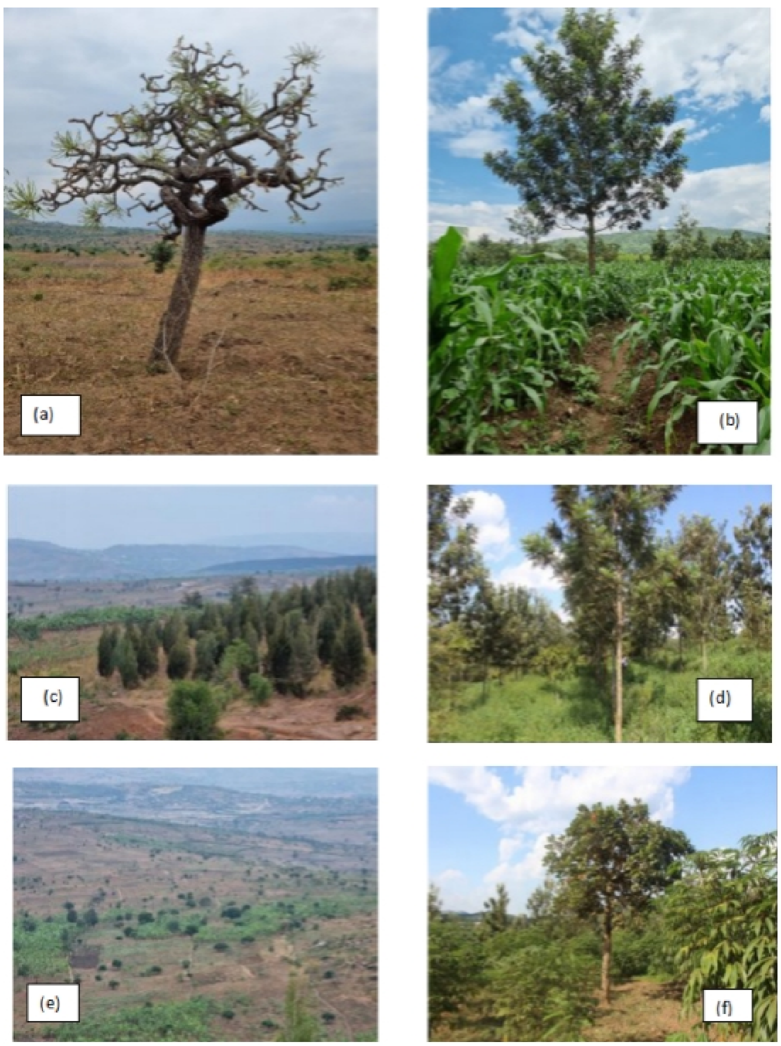

Figure 1

Examples of traditional agroforestry practices inperi-urban Kigali and eastern province of Rwanda. Note spatial arrangement of the woody component (a) Remnant and retained savanna tree after conversion of forest to farmland; (b) Patches of corn and soybeans under an isolated exotic tree (Grevillea robusta); (c) Woodlots of exotic tree species (Callitris carotrysis) surrounded by farmland; (d) Peas under trees (G. robusta) in rows – alley cropping on a conservation agricultural cropland; (e) Patches of banana plantation and scattered wooded trees in the farmland; (f) Patch of cassava under a native tree (Erytrina abysinica). All pictures come from eastern province of Rwanda.

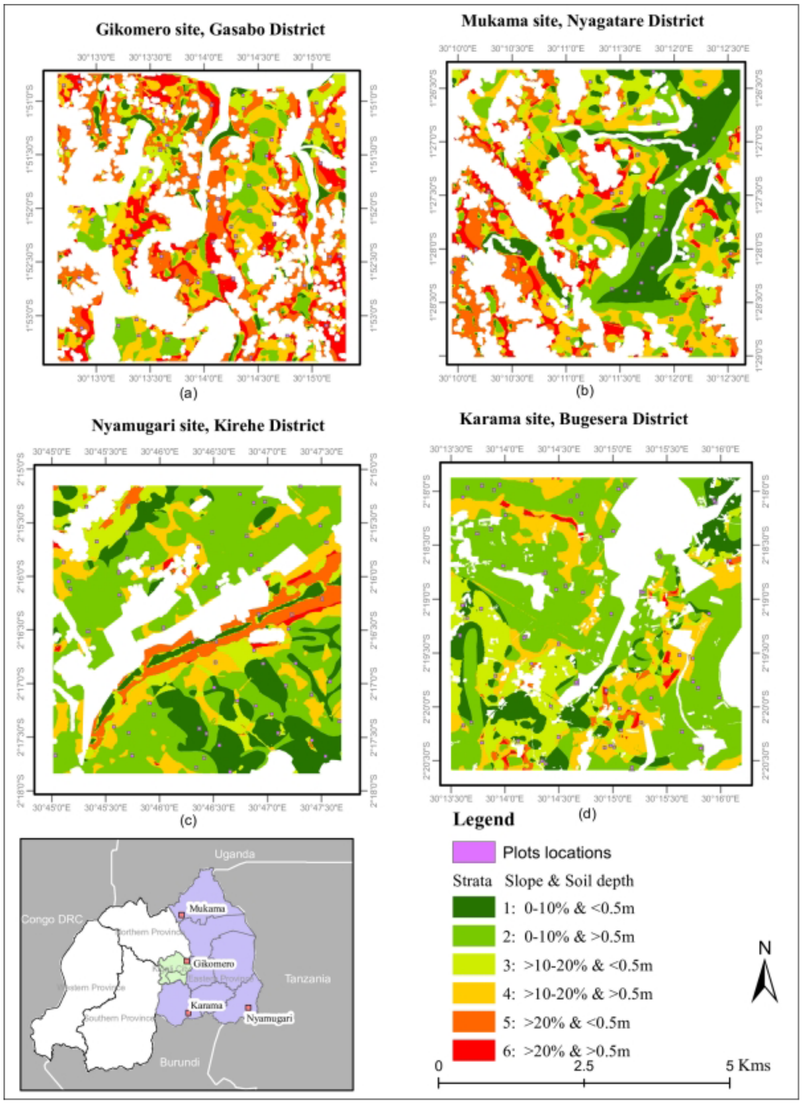

Figure 2

Maps of the four landscapes (5kmx5km window, each) and map of Rwanda showing the location of the studied agricultural landscapes selected in peri urban Kigali and in the east province of Rwanda. The four panels represent maps of the strata in each landscape based on slope and soil depth. Random plot locations in each stratum for each landscape are indicated in purple. Six slope and soil-depth stratawere identified. (a) Gikomero landscape in Gasabo District, (b) Mukama landscape in Nyagatare District, (c) Karama landscape in Bugesera District and (d) Nyamugari landscape in Kirehe District

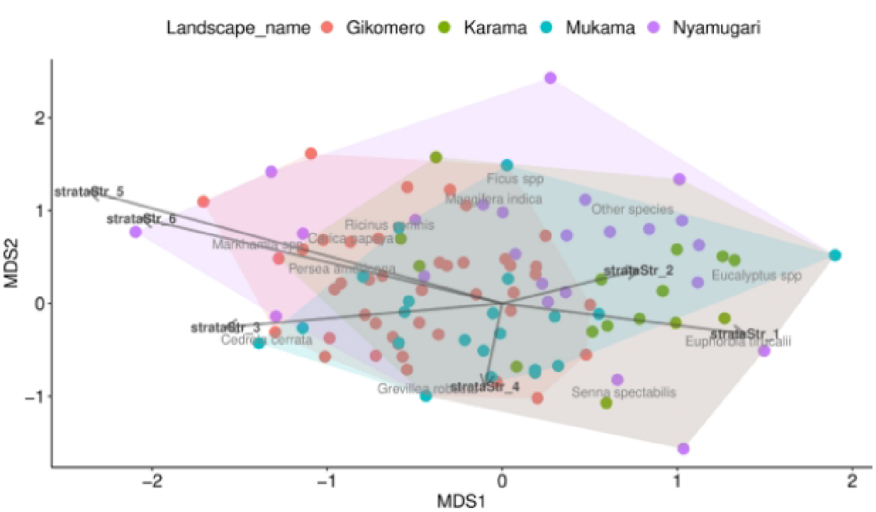

Figure 3

NMDS of species composition for the four landscapes across six strata. The violet polygon represents “Nyamugari” landscape, the green “Karama” landscape, the blue “Mukama” landscape, and the orange represent “Gikomero” landscape. *The dots with different colors represent plots within each specific landscape. The arrows indicate the variables characterizing the six strata (slope and soil depth). The eleven most frequent tree species are displayed in the figure: Carica papaya, Cedrela cerrata, Eucalyptus spp, Euphorbia tirucalii, Ficus spp, Grevillea robusta, Mangifera indica, Markhamia spp, Persea americana, Ricinus communis, Senna spectabilis and other species (Table 2).*

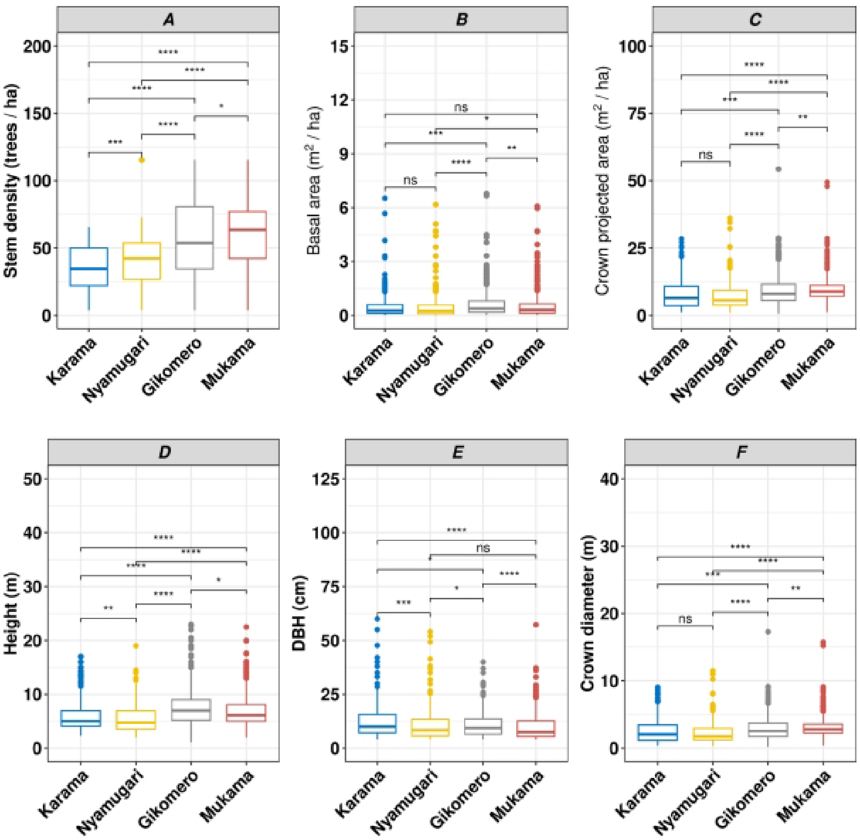

Figure 4

*Comparison of the plot-level tree structural attributes across the four landscapes. The stars associated to each panel indicate significant levels (p <0.05 0****0.001***0.005**0.01*0.05)*

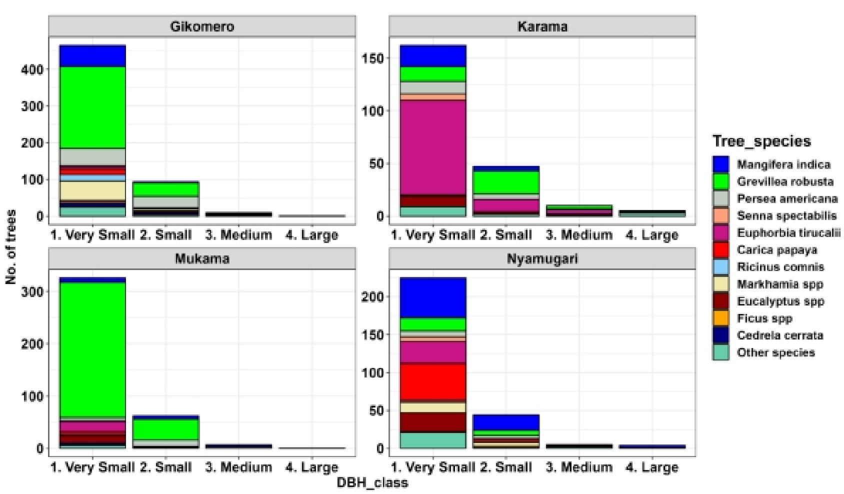

Figure 5

A comparison of diameter at breast height (DBH) size class distribution for the eleven most dominant tree species viewed all together within and across landscapes. The y-axes display the number of individuals counts. The x-axes display size class distribution across landscapes classified into four categories. DBH classes in cm are 1=Very small: ≤ 15 DBH); 2= Small: DBH 16 to 27; 3=Medium: DBH 28 to 39; 4=Large: DBH ≥40.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementinformationTreeoccurrence.docx