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Diversity, structure, and carbon storage of Rau catchment forest reserve in Moshi District, Tanzania

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Abstract. *Mwakalukwa EE, Masisi B. 2024. Diversity, structure, and carbon storage of Rau catchment forest reserve in Moshi District, Tanzania. Asian J For 9: 1-11.* The effects of anthropogenic activities and the dominance of exotic tree species on the Rau Catchment Forest Reserve (RCFR) in Moshi District, northern Tanzania, have been poorly documented. This study assessed (i) the current status of species composition, stand structure, and diversity, (ii) threats to biodiversity posed by anthropogenic activities and exotic tree species, and (iii) the carbon stock of RCFR. Data were gathered from 45 circular sample plots, identifying 29 woody plant species. The forest exhibited high woody species diversity (H'=2.91), with a density of 185±81 stems ha^{-1}, a standing volume of 405.75±227.16 m^3 ha^{-1}, and a basal area of 23.05±12.37 m^2 ha^{-1}. Evidence of human activities, particularly tree cutting and the dominance of exotic species, was prevalent, with illegal harvesting affecting 23 species. The mean above-ground and below-ground carbon stocks were estimated at 107.48±61.28 Mg C ha^{-1} and 21.50±12.26 Mg C ha^{-1}, respectively. The high diversity of woody species suggests that the forest may be recovering from past illegal logging. However, the increasing dominance of exotic species highlights the urgent need for measures to control their spread.

Keywords: Anthropogenic activities, biodiversity, exotic species, groundwater forests, urban forests

INTRODUCTION

Forests play a crucial role in global well-being by providing diverse ecosystem goods and services, including biodiversity conservation, climate regulation, economic resources, air and water purification, and recreational and aesthetic benefits (Aju et al. 2015; Bhatta et al. 2015; FAO 2022, 2024). In urban environments, forests contribute significantly to human well-being by mitigating air pollution, improving air quality, sequestering carbon to address climate change, reducing stormwater runoff, lowering urban temperatures, and offering green spaces for recreation (Patarkalashvili 2017; Massawe et al. 2019; Bushesha 2020; Pataki et al. 2021; Dickinson and Ramalho 2022; O'Brien et al. 2022).

Despite their importance, urban-proximate forests face numerous challenges (Güneralp et al. 2017). These include encroachment and loss of forest areas due to urban expansion into ecologically significant regions (Mutuga 2009; Addae and Oppelt 2019; Massawe et al. 2022), forest degradation resulting from unsustainable wood utilization leading to a decline in ecosystem services (Kilcullen et al. 2015; Sembosi 2019), and complete deforestation for conversion to alternative land uses (Güneralp et al. 2017; Massawe et al. 2019). Biodiversity loss occurs through habitat fragmentation, the disappearance of rare species, and reduced habitat quality caused by edge effects (Wade et al. 2003; McKinney 2008; Massawe et al. 2022). Illegal activities such as logging, mining, cultivation, and fire further open the canopy, facilitating the invasion and spread of non-native species. These invasive species disrupt biodiversity, alter forest structure, and reduce the provision of ecosystem services (Mavimbela et al. 2018; Kilawe et al. 2023). The replacement of natural forests with exotic species, which typically store less carbon, further diminishes the carbon sequestration capacity of these forests (Agboola et al. 2021).

Carbon stock assessments are critical for informed management and policy development, as forests are pivotal in climate regulation by reducing atmospheric CO_2 concentrations (Joshi et al. 2021). Accurate carbon stock data enable forest managers to negotiate favorable carbon credit terms, generate revenue for conservation, and strengthen their positions in global carbon markets (Biadgligne et al. 2022; Daba et al. 2022).

The Rau Catchment Forest Reserve (RCFR), located approximately 3 km from the Moshi municipality center in the Kilimanjaro region of Tanzania (Falck and Roponen 1994), exemplifies urban-adjacent forests under threat. Surrounded by six villages, RCFR faces challenges such as agricultural expansion, grazing, illegal logging, and the dominance of exotic tree species (Lovett and Poc's 1993; Falck and Roponen 1994; Mkiramweni 2015; Mhache 2019; Güneralp et al. 2017; Massawe et al. 2022). However, the extent of these impacts on forest biodiversity, structure, and function remains unclear. Understanding these effects is essential for biodiversity conservation and habitat management planning.

This study hypothesized that anthropogenic activities and the spread of exotic tree species negatively impact species diversity and forest structure, thereby reducing the forest's carbon storage and sequestration capacity (Agboola et al. 2021; Kilawe et al. 2023). The study aimed to evaluate the condition of RCFR under the influence of anthropogenic activities and exotic species and to estimate its current carbon stock. The specific objectives were to assess the status of (i) species composition and diversity of living and harvested trees, including indigenous and exotic species, (ii) stand structure of living and harvested trees, (iii) threats posed by exotic tree species to indigenous species, and (iv) above- and below-ground biomass and carbon stock of RCFR.

MATERIALS AND METHODS

Study area

Rau Catchment Forest Reserve (RCFR) is situated in Moshi District, Kilimanjaro Region, at coordinates 3°23' S and 37°22' E (Figure 1). Established in 1951 (GN. No. 127 of 25/5/1951) with an initial area of 1,427 ha, RCFR's boundaries were later adjusted to its current 570 ha due to extensive illegal logging during the late 1950s (Rogers 1983; Lovett and Poc′s 1993; Falck and Roponen 1994). The reserve lies at an elevation of 730-765 meters above sea level and receives an average annual rainfall of 870 mm, with a dry season spanning from June to February. Its soil is volcanic in origin, comprising alluvial sand and loam, and enriched with gleysols and fluvisoils (Lovett and Poc′s 1993).

RCFR is classified as a lowland, groundwater forest with characteristics of riverine and freshwater swamp forest types (Hermansen et al. 1985). It is also described as a tropical ombrophilous alluvial swamp forest (Falck and Roponen 1994), supported by a high water table that sustains semi-deciduous and swamp vegetation. The forest exhibits greater ecological affinities to Afromontane regions than to the Zanzibar-Inhambane Regional Mosaic (Falck and Roponen 1994). Its catchment function is significant, supplying water for irrigation of approximately 50,000 ha of rice farms in the dry lowland areas south of Mt. Kilimanjaro (Falck and Roponen 1994).

Human pressure on RCFR began as early as the 1950s, significantly altering the species structure and composition (Lovett and Poc′s 1993; Rogers 1983; Falck and Roponen 1994). In response, part of the degraded forest was rehabilitated through reforestation with exotic species during the 1950s (Lovett and Poc′s 1993). Logging was officially prohibited in the early 1980s as a conservation measure (Rogers 1983; Falck and Roponen 1994). About 216 ha of plantations were established within the reserve, including 10 ha of *Prioria msoo* (Harms) Breteler. Only 50 ha of natural forest remain intact.

Plantation species include *Tectona grandis* L.f., *Cedrela odorata* L., *Cedrela mexicana* M.Roem, *Lagerstroemia speciosa* (L.) Pers, *Eucalyptus* spp., *Cassia* sp., *Gmelina arborea* Roxb. ex Sm, and *Senna siamea* (Lam.) H.S. Irwin and Barneby. Among these, *G. arborea*, *S. siamea*, and *T. grandis* have become dominant (Lovett and Poc′s 1993; Mhache 2019). These exotic species contribute to ongoing ecological challenges in the reserve.

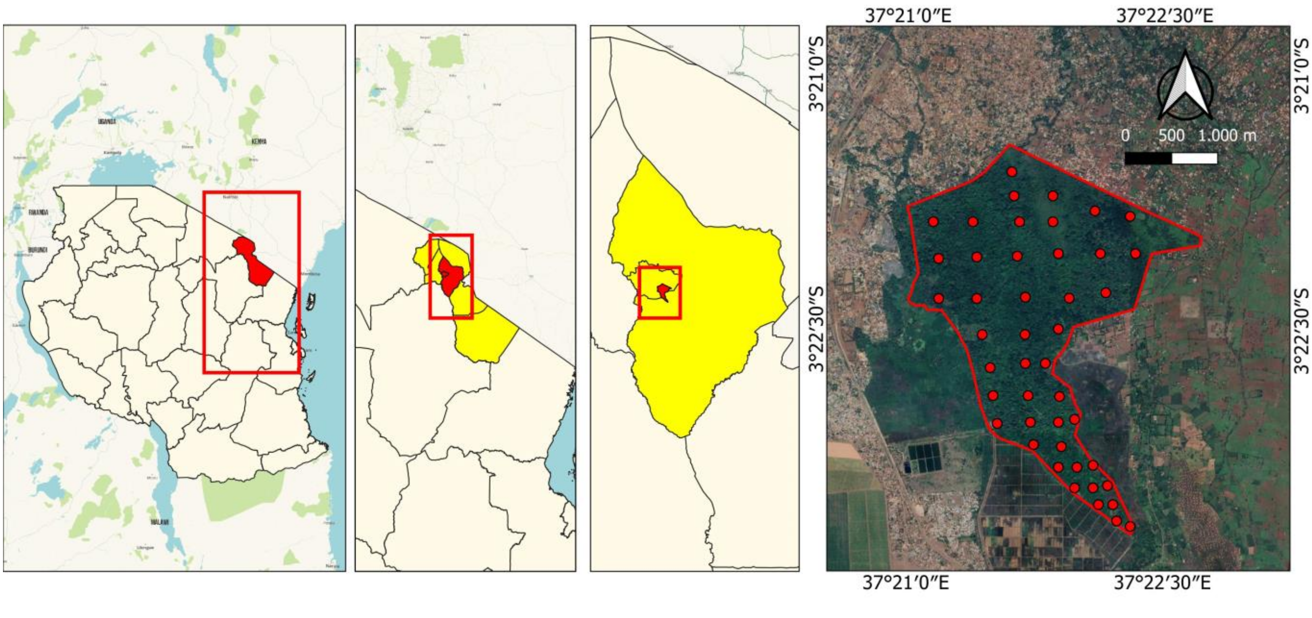

Figure 1. Map of Moshi District, Tanzania, showing the location of a lowland groundwater forest of Rau Catchment Forest Reserve (RCFR) and the layout of sample plots in the reserve (filled circles)

Data collection

A field survey was conducted in November 2017, utilizing 45 circular-shaped sample plots, each covering an area of 0.071 ha with a radius of 15 m. Circular plots were chosen for their ease of implementation, reduced edge effects, and minimized counting errors for border trees during inventory (Krebs 1989). A sampling intensity of 0.56% was adopted for this survey, aligning with the range of 0.5 to 0.7% recommended by Synnott (1979) for tropical natural forest inventories. This sampling intensity yielded 45 plots, deemed sufficient based on time constraints, inventory objectives, and resource availability (Synnott 1979; Mwakalukwa et al. 2023).

The sample plots were systematically distributed at 250 m intervals along transects spanning the 570 ha of the Rau Catchment Forest Reserve (RCFR). This systematic design ensured an even distribution of plots throughout the forest, minimizing bias and enabling a comprehensive assessment of forest composition. Within each plot, the following measurements were recorded: (i) Diameter at Breast Height (DBH): Measured for all trees with DBH ≥ 5 cm, using diameter tape or calipers depending on tree size, at 1.3 m above ground; (ii) Total Height and Basal Diameter: Recorded for three selected sample trees (small, medium, and large) at 15 cm above ground to capture size variation within species. Total height was measured with a Suunto hypsometer; (iii) Stump Diameter: Measured for all stumps with a diameter ≥ 5 cm, at 15 cm above ground.

The three sample trees within each plot were selected based on predefined diameter ranges to represent the existing size variation among tree species in the forest. Plant species identification was conducted in the field to ensure accurate taxonomic data. This methodical approach enabled a detailed and systematic inventory of the RCFR's structural and compositional attributes.

Data analysis

The data analysis focused on species richness, diversity, forest structure, and carbon stock across the 45 study plots. Total species richness was computed as the total number of species observed (Kent 2012). Species diversity was determined using the Shannon-Wiener diversity index, calculated as (H') = $-\sum Pi*(\ln(Pi))$, where: Pi represents the relative abundance of each species, calculated as the proportion of individuals of a given species to the total number of individuals (Ni) in the plot (ni/N), and ln denotes the natural logarithm (Kent 2012; Agboola et al. 2021; Ayele et al. 2024). The values of H' typically fall between 1.5 and 3.5, rarely exceeding 4.5 (Kent 2012). An H' value greater than 2 suggests medium to high diversity, according to Magurran (2004), with higher values indicating greater species diversity.

The Importance Value Index (IVI) was calculated as the sum of relative frequency, relative density, and relative dominance (basal area), expressed as a percentage (Kent and Coker 1992; Agboola et al. 2021; Ayele et al. 2024). Forest structure was analyzed by determining stem density, basal area, and volume for each species, categorized by diameter class (Mwakalukwa et al. 2023; Ayele et al. 2024). To predict tree heights (Ht) of non-sampled trees, data on Ht from three trees of different sizes per plot (small, medium, and large) were used. A non-linear regression equation was developed (Winsor 1932; Mwaluseke et al. 2023).

Tree volume was estimated using DBH and Ht data, with volume equations applied at plot and forest levels. Additionally, biomass estimation incorporated DBH, Ht, and wood basic density (WD). Biomass was then used to estimate carbon stock at both plot and forest levels. Models from Mugasha et al. (2016) for lowland forests in Tanzania were applied to estimate forest volume and biomass using an equation from the Rondo site. Biomass was converted into carbon density per hectare, with below-ground biomass estimated as 20% of total above-ground biomass. The equations used were:

Height (m) or Ht (m) = $(-0.00365\times DBH^2) + (0.7916\times DBH) + 3.5451$ ($R^2 = 0.79$; AIC =509; n = 122; Ht range: 4m to 47.8m with mean 21 m)

Volume (m^3 $tree^{-1}$) = $0.000076 \times DBH^{2.3488}\times Ht^{0.3848}$ ($R^2 = 0.95$; RMSE = 0.90; AIC=91.648)

Biomass (kg $tree^{-1}$) = $0.07511\times (WD \times DBH^2 \times Ht)^{0.9477}$ (R^2= 0.92; RMSE= 462.47; AIC= 396.58)

Where:
DBH: Diameter at Breast Height (cm)
Ht: Total tree height (m)
WD: Wood Basic Density (g cm^{-3})
RMSE: Root Mean Square Error
AIC: Akaike's Information Criterion
R^2: Coefficient of determination.

Wood basic density values for each species were sourced from Reyes et al. (1992), Brown (1997), and Orwa et al. (2009). Carbon stock was calculated per hectare (Mg C ha^{-1}) by multiplying biomass with a conversion factor of 0.49 (Manyanda et al. 2020). All data analyses were performed using Excel spreadsheets and R (version 4.2.0).

RESULTS AND DISCUSSION

Species composition and diversity

A total of 29 tree and shrub species, with diameters ranging from 5 to 240 cm, were identified in RCFR, belonging to 28 genera and 15 plant families (Table 1). Of these species, trees contributed 93% (13 plant families), while shrubs accounted for 7% (2 plant families). The Fabaceae family had the highest number of tree species (19%), followed by the Myrtaceae family (15%), while the shrub species were primarily from the Boraginaceae and Salicaceae families. The most frequently encountered species were *Macaranga kilimandscharica* Pax (49% of plots), *Tabernaemontana ventricosa* Hochst. ex A.DC. (40%), *Ficus sycomorus* L. (36%), *Trichilia emetica* Vahl (31%), and *Milicia excelsa* (Welw.) C.C.Berg (29%) (Table 1). The average number of species per plot was four, with a range of 1 to 9 species per plot (Figure 2). Among the ten most important species, based on the Importance Value Index (IVI) and Shannon-Wiener diversity index (H') scores, *Gmelina arborea*, *Senna siamea*, and *Tectona grandis* emerged as key species (Table 1).

The study identified a total of 23 tree and shrub species with basal diameters ranging from 5 to 104 cm, belonging to 21 genera and 14 plant families in the Rau Catchment Forest Reserve (RCFR). Of these, trees comprised 91% (12 plant families) and shrubs 9% (2 plant families). The most abundant families in terms of harvested species were Fabaceae (17%) and Myrtaceae (13%). *Senna siamea* (exotic) was the most frequent species among the harvested individuals, occurring in 16% of plots, followed by *M. excelsa* (11%), *M. kilimandscharica* (11%), and *Cordia africana* (11%). *G. arborea*, *S. siamea*, and *T. grandis* were also important species according to the Importance Value Index (IVI) and Shannon-Wiener diversity index (H').

The species richness of 29 tree and shrub species reported in this study (9 exotic and 20 indigenous) is lower than that of other tropical lowland, groundwater, riverine, and freshwater swamp forests, with the exception of Kacholi (2019). The lower species richness could be attributed to the smaller number of sample plots used (45 plots) and the applied diameter limit of ≥ 5 cm. The results, however, align closely with those presented by Mkiramweni (2015), who found 38 species in the same forest using more than twice the number of plots (114). In contrast, Falck and Roponen (1994) identified 92 species across all vascular plants with no diameter limit. This suggests that RCFR has relatively low species richness, which may be influenced by ongoing illegal activities and the dominance of exotic species, which suppress the regeneration of indigenous species (Mhache 2019). According to Mkiramweni (2015), major threats to the RCFR vegetation include firewood collection (25.5%), illegal timber harvesting (14.3%), pole cutting (11.7%), fodder collection (9%), grazing (8.2%), and encroachment (7.9%). The reported harvested stem density of 55±35 stems ha^{-1} in this study supports the occurrence of these anthropogenic activities.

The lower Shannon-Wiener index (H'=2.91) for trees and shrubs in this study compared to other tropical forests suggests that the RCFR has been impacted by past disturbances (Lovett and Poc′s1993; Mkiramweni 2015). Kent (2012) notes that a forest is considered rich when its H' value exceeds 3.5, while a value above 2 suggests medium to high diversity (Magurran 2004). Therefore, the H' value of 2.91 in this study indicates that RCFR is a relatively high-diversity forest with an even distribution of species.

Species from the genera *Milicia*, *Macaranga*, and *Cordia* were the most frequently harvested, valued for timber, charcoal, firewood, and medicine (Lovett and Poc′s 1993; Mkiramweni 2015). Interestingly, the rare species *P. msoo* was also included in the list of harvested species, prized for its straightness and durability, particularly in broom handle production. The frequent harvesting of *S. siamea*, an exotic species, highlights how human preferences shape the composition of harvested tree species. A targeted tree planting program could help meet local needs and reduce pressure on the forest by encouraging the cultivation of preferred species outside the reserve.

Stand structure

The total mean stem density, basal area, and volume for standing and harvested trees and shrubs in RCFR are detailed in Tables 1 and 2. Regarding stem density, four exotic species—*S. siamea*, *G. arborea*, *T. grandis*, and *Eucalyptus* sp.—dominate the forest. Exotics contribute 63 ± 36 stems ha^{-1} (34%) to the total stem density of standing trees and shrubs, while indigenous species contribute 122±45 stems ha^{-1} (66%) (Figure 3, Table 1). Exotic species predominantly occupy the lower diameter classes (below 30.0 cm), although a few individuals are found in diameter classes greater than 30.0 cm (Figure 4).

For stumps, *G. arborea* (14 stems ha^{-1}), *S. siamea* (12 stems ha^{-1}), and *T. grandis* (8 stems ha^{-1}) are the most abundant exotic species (Table 2). The distribution of trees across size classes follows the typical reverse J shape, with a higher number of smaller individuals (Figure 5). Most of the harvested individuals also fall below the 30.0 cm basal diameter, and the majority of these harvested individuals are exotic species (Figure 6).

In terms of basal area, the trend in stem density is reflected similarly, with exotic trees and shrubs occupying 5.93±4.28 m² ha^{-1} (26%) of the basal area, while indigenous trees and shrubs occupy 17.12±8.09 m² ha^{-1} (74%) (Table 1). *G. arborea*, *Eucalyptus* sp., and *S. siamea* contributed the most to the basal area of standing exotic species (Figure 7), while the species contributing most to the basal area of stumps are shown in Figure 8. The distribution of trees to size classes follows a normal "J" shape (Figure 9), indicating that trees with a diameter greater than 70.1 cm contribute significantly to the per-hectare basal area of the forest.

In terms of volume, the species contributing most to the stand volume of standing individuals were *F. sycomorus* (31%), *G. arborea* (11%), *M. excelsa* (10%), and *Newtonia buchananii* (8%) (Table 1). Exotic species contributed 22% (88.38 ± 66.60 m³ ha^{-1}), while indigenous trees and shrubs contributed 78% (317.37 ± 160.57 m³ ha^{-1}) (Table 1). As with basal area, most exotic species occur in the lower diameter classes (below 30.0 cm), though a few are found in diameter classes greater than 30.0 cm (Figure 4). The distribution of standing trees to size classes follows a near-normal "J" shape, with trees in larger diameter classes (>40.1 cm) contributing significantly to the mean total standing volume of the forest (Table 1).

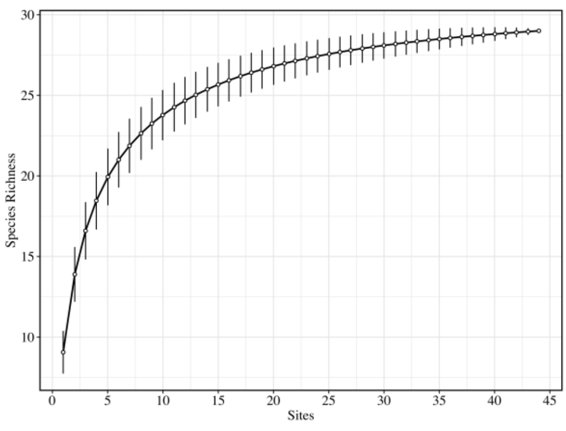

Figure 2. Species accumulation curve of tree species in Rau Catchment Forest Reserve (RCFR), Moshi District, Tanzania. The curve depicts the expected number of species as a function of the sampled area, with the upper and lower bounds representing the 95% confidence intervals

Table 1. List of standing tree and shrub species with a minimum DBH of 5 cm sorted by Importance Value Index (IVI) identified in Rau Catchment Forest Reserve (RCFR), Moshi District, Tanzania

Species name	Plant family	Habit	Category	Frequency (%)	*Rf (%)	RDe (%)	RDo (%)	IVI	*H'*	Density (stems ha^{-1})	Basal area (m^2 ha^{-1})	Stand Volume (m^{3}ha^{-1})	AGC (Mgha^{-1})	BGC (Mgha^{-1})
Ficus sycomorus L.	Moraceae	Tree	IND	36	8.5	5.3	25.1	38.8	0.16	10±3	5.78±2.23	124.31±50.62	18.56±7.37	3.71±1.47
Macaranga kilimandscharica Pax	Euphorbiaceae	Tree	IND	49	11.6	8.2	7.2	27.0	0.20	15±3	1.66±0.47	25.76±8.00	6.28±1.92	1.26±0.38
Tabernaemontana ventricosa Hochst. ex A.DC.	Apocynaceae	Tree	IND	40	9.5	15.0	2.0	26.5	0.28	28±8	0.45±0.20	4.02±2.06	1.92±0.97	0.38±0.19
Gmelina arborea Roxb. ex Sm.	Lamiaceae	Tree	EXT	9	2.1	8.3	11.1	21.5	0.21	15±9	2.55±1.84	44.18±33.15	11.00±8.03	2.20±1.61
Senna siamea (Lam.) H.S.Irwin & Barneby	Fabaceae	Tree	EXT	24	5.8	10.7	4.3	20.9	0.24	20±7	0.99±0.37	11.64±4.48	5.06±1.94	1.01±0.39
Milicia excelsa (Welw.) C.C.Berg	Moraceae	Tree	IND	29	6.9	4.8	9.0	20.6	0.15	9±3	2.07±1.07	39.56±23.48	12.65±6.68	2.53±1.34
Trichilia emetica Vahl	Meliaceae	Tree	IND	31	7.4	5.8	2.1	15.3	0.16	11±3	0.49±0.21	6.42±3.26	2.38±1.18	0.48±0.24
Syzygium guineense (Willd.) DC.	Myrtaceae	Tree	IND	13	3.2	4.6	5.0	12.8	0.14	8±5	1.15±0.59	21.38±11.38	8.67±4.51	1.73±0.90
Tectona grandis L.f.	Lamiaceae	Tree	EXT	9	2.1	7.2	3.2	12.4	0.19	13±8	0.73±0.48	9.04±6.31	3.11±2.17	0.62±0.43
Newtonia buchananii (Baker) G.C.C.Gilbert & Boutique	Fabaceae	Tree	IND	11	2.6	2.0	6.9	11.6	0.08	4±2	1.58±0.93	31.68±18.96	8.35±4.92	1.67±0.98
Bridelia micrantha (Hochst.) Baill.	Phyllanthaceae	Tree	IND	13	3.2	2.4	5.9	11.5	0.09	4±2	1.37±0.99	26.57±20.76	6.98±5.23	1.40±1.05
Eucalyptus sp.	Myrtaceae	Tree	EXT	2	0.5	4.4	5.9	10.8	0.14	8±8	1.35±1.35	19.62±19.62	7.21±7.21	1.44±1.44
Vachellia xanthophloea (Benth.) Banfi & Galasso	Fabaceae	Tree	IND	13	3.2	3.4	2.8	9.4	0.12	6±3	0.66±0.38	9.64±5.92	5.18±3.15	1.04±0.63
Sorindeia madagascariensis DC.	Anacardiaceae	Tree	IND	22	5.3	2.9	0.6	8.8	0.10	5±2	0.14±0.07	1.30±0.64	0.42±0.21	0.08±0.04
Albizia schimperiana Oliv.	Fabaceae	Tree	IND	13	3.2	1.5	3.8	8.5	0.06	3±1	0.88±0.45	16.55±9.30	4.54±2.43	0.91±0.49
Prioria msoo (Harms) Breteler	Fabaceae	Tree	IND	11	2.6	3.1	1.3	7.0	0.11	6±3	0.31±0.21	3.95±2.79	1.24±0.88	0.25±0.18
Croton macrostachyus Hochst. ex Delile	Euphorbiaceae	Tree	IND	18	4.2	1.7	0.9	6.8	0.07	3±1	0.20±0.09	2.42±1.11	0.77±0.35	0.15±0.07
Cordia africana Lam.	Boraginaceae	Shrub	IND	16	3.7	2.0	0.5	6.2	0.08	4±2	0.11±0.05	1.08±0.47	0.56±0.25	0.11±0.05
Rauvolfia caffra Sond.	Apocynaceae	Tree	IND	9	2.1	1.0	0.3	3.4	0.05	2±1	0.07±0.04	0.63±0.41	0.22±0.14	0.04±0.03
Syzygium cumini (L.) Skeels	Myrtaceae	Tree	IND	9	2.1	1.0	0.3	3.4	0.05	2±1	0.06±0.04	0.61±0.36	0.27±0.16	0.05±0.03
Cedrela odorata L.	Meliaceae	Tree	EXT	9	2.1	1.0	0.1	3.3	0.05	2±1	0.03±0.02	0.23±0.16	0.06±0.04	0.01±0.01
Casuarina equisetifolia L.	Casuarinaceae	Tree	EXT	7	1.6	0.5	0.7	2.8	0.03	1±1	0.17±0.11	2.60±1.87	1.28±0.91	0.26±0.18
Fagaropsis angolensis (Engl.) H.M.Gardner	Rutaceae	Tree	IND	7	1.6	0.7	0.5	2.8	0.03	1±1	0.11±0.07	1.36±0.90	0.37±0.24	0.07±0.05
Dovyalis caffra (Hook. f. & Harv.) Warb.	Salicaceae	Shrub	EXT	4	1.1	0.7	0.3	2.0	0.03	1±1	0.06±0.06	0.63±0.62	0.20±0.20	0.04±0.04
Mangifera indica L.	Anacardiaceae	Tree	EXT	4	1.1	0.7	0.1	1.9	0.03	1±1	0.03±0.02	0.20±0.15	0.07±0.06	0.01±0.01
Psidium guajava L.	Myrtaceae	Tree	EXT	4	1.1	0.3	0.1	1.5	0.02	1±0	0.02±0.02	0.24±0.24	0.09±0.09	0.02±0.02
Markhamia obtusifolia (Baker) Sprague	Bignoniaceae	Tree	IND	2	0.5	0.3	0.1	0.9	0.02	1±1	0.01±0.01	0.11±0.11	0.04±0.04	0.01±0.01
Cinchona sp.	Rubiaceae	Tree	IND	2	0.5	0.2	0.0	0.7	0.01	0±0	0.00±0.00	0.01±0.01	0.00±0.00	0.00±0.00
Kigelia africana (Lam.) Benth.	Bignoniaceae	Tree	IND	2	0.5	0.2	0.0	0.7	0.01	0±0	0.00±0.00	0.02±0.02	0.01±0.01	0.00±0.00
Total				420	100	100	100	300	2.91	185±81	23.05±12.37	405.75±227.16	107.48±61.28	21.50±12.26

Note: * Rf = Relative frequency, RDe = Relative density, RDo = Relative dominance (basal area), *H'* = Shannon-Wiener diversity index, AGC = Above Ground Carbon (mean ± SE), BGC = Below Ground Carbon (mean ± SE), density (mean ± SE), Basal area (mean ± SE), Stand volume (mean ± SE). Plot size = 15 m radius. SE = Standard error. EXT = Exotic, IND = Indigenous

Table 2. List of harvested tree and shrub species with a minimum basal diameter of 5 cm sorted by Importance Value Index (IVI) identified in Rau Catchment Forest Reserve (RCFR), Moshi District, Tanzania

Species name	Plant family	Habit	Category	Frequency (%)	*Rf (%)	RDe (%)	RDo (%)	IVI	*H'*	Density (stems ha^{-1})	Basal area (m^2 ha^{-1})	Stand Volume ($m^3 ha^{-1}$)
Gmelina arborea Roxb. ex Sm.	Lamiaceae	Tree	EXT	7	5.6	24.7	32.9	63.1	0.35	14±10	1.39±0.98	0.77±0.54
Senna siamea (Lam.) H.S.Irwin & Barneby	Fabaceae	Tree	EXT	16	13.0	21.3	18.5	52.8	0.33	12±5	0.78±0.46	0.33±0.17
Tectona grandis L.f.	Lamiaceae	Tree	EXT	7	5.6	14.4	11.2	31.2	0.28	8±5	0.47±0.32	0.27±0.18
Macaranga kilimandscharica Pax	Euphorbiaceae	Tree	IND	11	9.3	4.6	4.1	17.9	0.14	3±1	0.17±0.11	0.17±0.12
Cordia africana Lam.	Boraginaceae	Shrub	IND	11	9.3	4.0	4.3	17.6	0.13	2±1	0.18±0.11	0.10±0.06
Bridelia micrantha (Hochst.) Baill.	Phyllanthaceae	Tree	IND	7	5.6	4.0	6.7	16.3	0.13	2±1	0.28±0.26	1.00±0.98
Milicia excelsa (Welw.) C.C.Berg	Moraceae	Tree	IND	11	9.3	4.0	2.0	15.3	0.13	2±1	0.08±0.04	0.04±0.02
Albizia gummifera (J.F.Gmel.) C.A.Sm.	Fabaceae	Tree	IND	2	1.9	1.7	6.5	10.1	0.07	1±1	0.28±0.28	0.04±0.04
Eucalyptus sp.	Myrtaceae	Tree	EXT	2	1.9	3.4	4.7	10.0	0.12	2±2	0.20±0.20	0.08±0.08
Tabernaemontana ventricosa Hochst. ex A.DC.	Apocynaceae	Tree	IND	7	5.6	2.9	0.3	8.7	0.10	2±1	0.01±0.01	0.01±0.00
Trichilia emetica Vahl	Meliaceae	Tree	IND	7	5.6	2.9	0.3	8.7	0.10	2±1	0.01±0.01	0.01±0.00
Prioria msoo (Harms) Breteler	Fabaceae	Tree	IND	7	5.6	1.7	0.4	7.7	0.07	1±1	0.02±0.01	0.01±0.00
Croton macrostachyus Hochst. ex Delile	Euphorbiaceae	Tree	IND	4	3.7	1.1	1.8	6.6	0.05	1±0	0.07±0.07	0.02±0.01
Vachellia xanthophloea (Benth.) Banfi & Galasso	Fabaceae	Tree	IND	2	1.9	0.6	3.2	5.6	0.03	0±0	0.14±0.14	0.04±0.04
Melanopsidium nigrum Colla	Rubiaceae	Tree	IND	2	1.9	2.3	0.6	4.7	0.09	1±1	0.02±0.02	0.00±0.00
Markhamia obtusifolia (Baker) Sprague	Bignoniaceae	Tree	IND	2	1.9	1.1	1.0	4.0	0.05	1±1	0.04±0.04	0.01±0.01
Cordia africana Lam.	Boraginaceae	Tree	IND	2	1.9	0.6	1.0	3.4	0.03	0±0	0.04±0.04	0.03±0.03
Syzygium guineense (Willd.) DC.	Myrtaceae	Tree	IND	2	1.9	1.1	0.2	3.2	0.03	0±0	0.00±0.00	0.00±0.00
Ficus sycomorus L.	Moraceae	Tree	IND	2	1.9	1.1	0.1	3.1	0.05	1±1	0.00±0.00	0.00±0.00
Sorindeia madagascariensis DC.	Anacardiaceae	Tree	IND	2	1.9	0.6	0.3	2.7	0.03	0±0	0.01±0.01	0.00±0.00
Euclea divinorum Hiern	Ebenaceae	Shrub	IND	2	1.9	0.6	0.1	2.5	0.03	0±0	0.00±0.00	0.00±0.00
Kigelia africana (Lam.) Benth.	Bignoniaceae	Tree	IND	2	1.9	0.6	0.0	2.5	0.03	0±0	0.00±0.00	0.00±0.00
Syzygium cumini (L.) Skeels	Myrtaceae	Tree	IND	2	1.9	0.6	0.0	2.4	0.05	1±1	0.01±0.01	0.01±0.01
Total				120	100	100	100	300	2.41	55±35	4.22±3.11	2.94±2.33

Note: * Rf = Relative frequency, RDe = Relative density, RDo = Relative dominance (basal area), *H'* = Shannon-Wiener diversity index, density (mean ± SE), Basal area (mean ± SE), Stand volume (mean ± SE). Plot size = 15 m radius. IND = Indigenous, EXT = Exotic

Table 3. Species richness, diversity, stem density, and basal area values observed in other studies from lowland, groundwater, riverine, and freshwater swamp forests

Reference	Location	Sample plots	Plots size (m)	Species richness	Plant families	*H'*	Density (stems ha^{-1})	Basal area (m^2ha^{-1})
Abdullah et al. (2021)	Freshwater swamp forest at Parit forest reserve in Malaysia	-	-	-	-	2.39	484	23.9
Agboola et al. (2021)	Lowland forests across Southwest (SW) Nigeria	6	25×25	55	-	2.55	770.67	23.23
Avila et al. (2021)	Six swamp forests in Southeastern Brazil	-	5×5	134 (range 29-59)	47	1.82, 2.07, 2.23, 2.28, 2.93, and 3.18	-	-
Banya et al. (2021)	Kangari Hills swamp forest reserve in Sierra Leone	15	10×10	58	30	3.63	367	33
Buragohain et al. (2023)	A lowland rain forest of Kakoi reserve forest in India	2	100×100	55	26	3.55, 3.68	582, 446	38.43, 32.63
Igu (2017)	Otuwe freshwater swamp forest in the Niger Delta in Nigeria	8	100×100	35	18	1.66	255	-
Kacholi (2013)	Kimboza lowland forest reserve in Tanzania	18	20×20	52	22	3.40	390	24
Kacholi (2014)	Kilengwe lowland forest reserve in Tanzania	18	20×20	67	26	4.02	276	7.1
Kacholi (2019)	Nongeni lowland forest reserve in Tanzania	20	20×25	24	11	2.67	751	10.8±2.6
Meragiaw et al. (2018)	Walga riparian vegetation in Ethiopia	50	10×50	99	45	3.55	356	-
Mkiramweni (2015)	Rau catchment forest reserve	114	10×50	38	22	2.99	306±12	30.1±2.5
Mligo (2015)	Namatimbili lowland riverine, coastal forest in Tanzania	-	20×50	85	31	1.64	-	73.8±21.5
Mligo (2016)	Wami river system in Tanzania at Kilosa site	-	-	-	-	1.63, 2.40, 2.55, 2.70 and 2.94	-	-
Rahmah et al. (2016)	Lowland forest in the Bukit Duabelas National Park, Indonesia	-	-	-	-	4.29	414	25.7
Yen and Cochard (2017)	Lowland evergreen rain forest of Nam Dong district in Central Vietnam	-	-	-	-	2.91	678	27
Our study	Rau catchment forest reserve	45	15	29	15	2.91	185±81	23.1±12.4

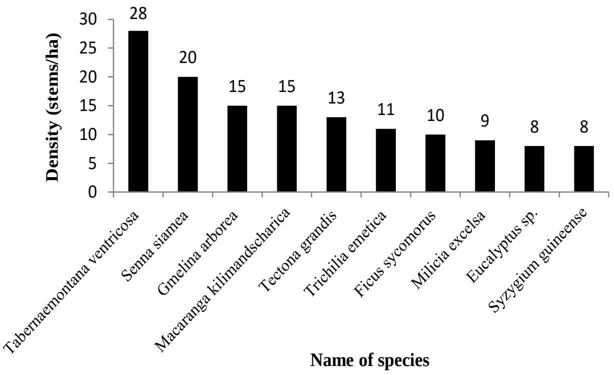

Figure 3. The 10 most abundant standing species with a high stem density were found in Rau Catchment Forest Reserve (RCFR), Moshi District, Tanzania

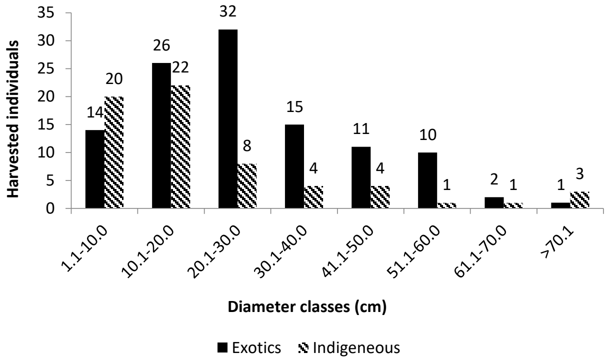

Figure 6. The distribution of harvested individuals of tree species and shrubs with ≥ 5 cm basal diameter by diameter class in Rau Catchment Forest Reserve (RCFR), Moshi District, Tanzania

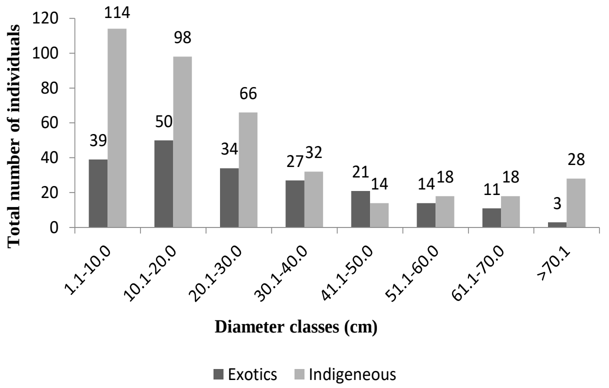

Figure 4. The distribution of total individual standing tree species and shrubs with ≥ 5 cm DBH by diameter class in Rau Catchment Forest Reserve (RCFR), Moshi District, Tanzania

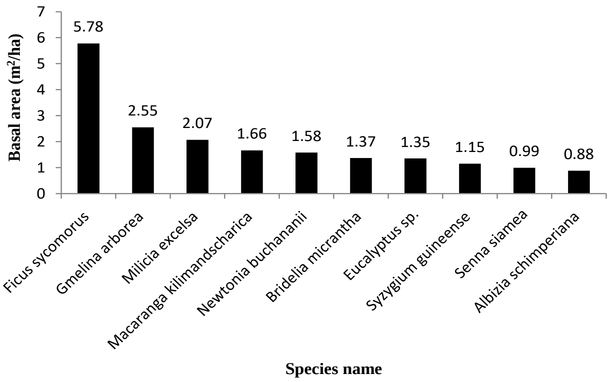

Figure 7. The 10 most abundant standing species with high basal area are found in Rau Catchment Forest Reserve (RCFR), Moshi District, Tanzania

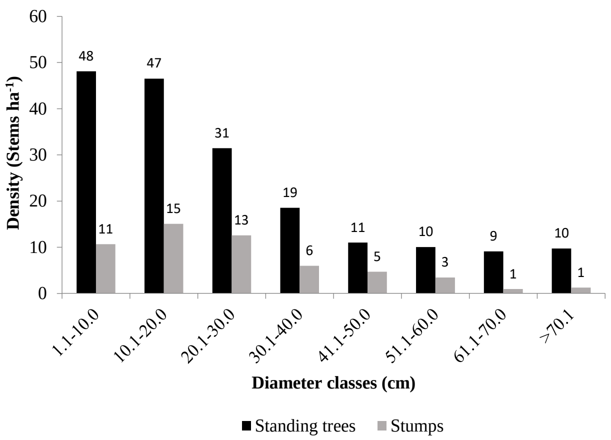

Figure 5. The distribution of density per hectare of standing tree species and shrubs with ≥ 5 cm DBH and stumps ≥ 5 cm basal diameter by diameter class in Rau Catchment Forest Reserve (RCFR), Moshi District, Tanzania

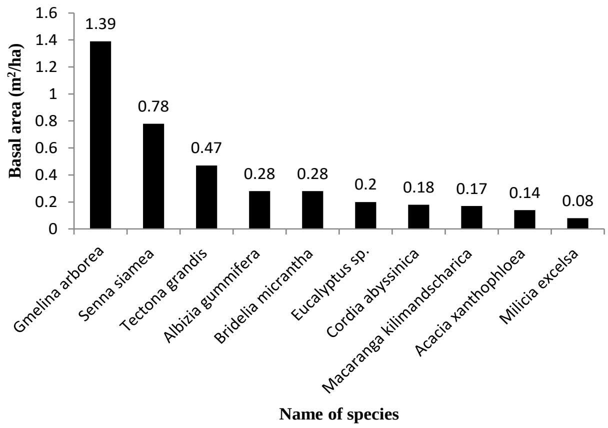

Figure 8. The 10 most abundant harvested species with high basal areas are found in Rau Catchment Forest Reserve (RCFR), Moshi district, Tanzania

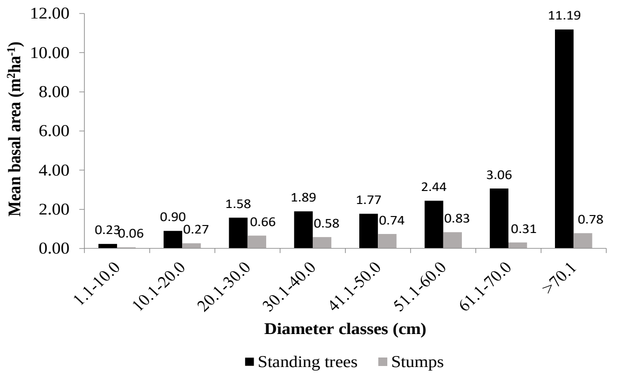

Figure 9. The distribution of basal area per hectare of standing tree species and shrubs with ≥ 5 cm DBH and stumps ≥ 5 cm basal diameter by diameter class in Rau Catchment Forest Reserve (RCFR), Moshi District, Tanzania

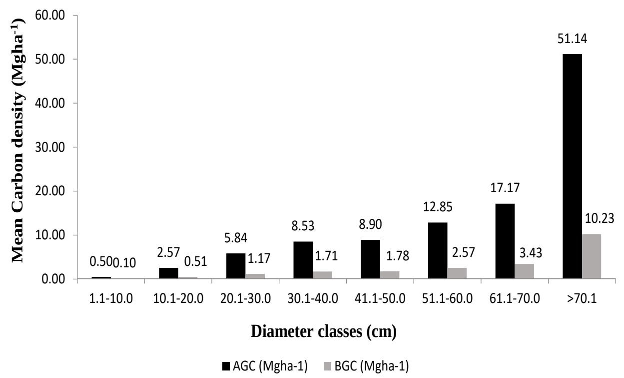

Figure 10. The distribution of above-ground and below-ground mean carbon density of standing tree species and shrubs ≥ 5 cm DBH by diameter class in Rau Catchment Forest Reserve (RCFR), Moshi district, Tanzania

For felled trees, the species contributing most to the volume were *Bridelia micrantha* (34%), *G. arborea* (26%), *S. siamea* (11%), and *T. grandis* (9%) (Table 2). The distribution of stumps to size classes shows that trees with a basal diameter greater than 40.1 cm contributed more to the mean total harvested volume in the forest.

Generally, all stand structure attributes of RCFR (stem density, basal area, and volume) appear lower when compared to other tropical lowland, groundwater, riverine, and freshwater swamp forests (Table 3), except for the stem density of 136 stems ha^{-1} reported by Mligo (2015) from the Namatimbili lowland riverine, coastal forest in Tanzania (Table 3). Banya et al. (2021) reported a volume value of 741.3 m^3 ha^{-1} from the Kangari Hills swamp forest reserve in Sierra Leone. The lower stem density observed in this study could be due to the impact of human activities, particularly excessive tree-cutting, which has reduced the total number of stems in the reserve. This also accounts for the lower basal area and stand volume recorded in the forest. The higher density, basal area, and volume reported in other studies may be attributed to the intact conditions of those forests, which promote the occurrence of many individuals of a particular species, including those in higher DBH classes. The normal reversed "J" shape shown by the diameter class distribution indicates the dominance of small trees, suggesting a good regeneration status (Figure 5).

The dominance of *S. siamea*, *G. arborea*, *T. grandis*, *Eucalyptus* sp., and *Casuarina equisetifolia* among the standing exotic species in terms of stem density, basal area, and stand volume indicates that these species are taking advantage of open spaces created by illegal logging and other anthropogenic activities to establish themselves and grow in large numbers (Falck and Roponen 1994; Mhache 2019) (Figure 4; Table 1). These species, except for *T. grandis*, have been documented as invasive elsewhere (Binggeli et al. 1998; Witt and Luke 2017; CABI 2018), and their ability to suppress the growth of other species poses a threat to the survival of indigenous tree species in the reserve (Falck and Roponen 1994). For instance, *T. grandis* has been observed to alter forest floor conditions by producing a thick cover of old leaves, which hampers regeneration of other species (Falck and Roponen 1994). Introducing foreign species carries the risk of uncontrolled spread, which may affect soil composition, light conditions, and underground vegetation, thereby altering the overall character of the forest. Therefore, it is crucial to investigate the regeneration patterns of local species under the canopy of these exotic species to assess whether they pose a threat to the sustainability of indigenous trees in the reserve and to understand the potential consequences if these threats are not addressed.

The analysis of diameter class distribution for all exotic and indigenous species reveals that the majority of exotic species are concentrated in the lower diameter classes (<30.0 cm), indicating they are replacing indigenous species and affecting ecological succession (Figure 4). This highlights the need for measures to control the dominance and spread of exotic species to allow for the regeneration of native forest species. Efforts to prevent illegal tree cutting, which opens up the forest canopy and facilitates the spread of exotic species, should be intensified (Mavimbela et al. 2018).

Biomass and carbon storage

The mean above-ground and below-ground biomass and carbon stocks for trees and shrubs with a diameter ≥5 cm found in RCFR are presented in Table 1. The tree species contributing most to the observed above-ground carbon density were *F. sycomorus* (17%), *M. excelsa* (12%), and *G. arborea* (exotic) (10%). These same species also contributed significantly to the observed below-ground carbon density. The biomass and carbon distribution across different diameter classes exhibited a near-normal "J" shape (Figure 10), with biomass and carbon increasing as diameter size increased. Approximately 95% of the biomass and carbon were stored in large diameter classes (>70.1 cm), indicating the presence of large trees within the reserve.

Indigenous species contributed a larger share (74%) to the total mean above-ground biomass and carbon stock compared to exotic species, which contributed 26% (Table 1). Among the indigenous species, *F. sycomorus*, *M. excelsa*, *Syzygium guineense* (Willd.) DC, *N. buchananii*, and *B. micrantha* contributed the most to the observed above-ground carbon density. On the other hand, the exotic species that contributed the most to the observed above-ground carbon density were *G. arborea*, *Eucalyptus* sp., *S. siamea*, and *T. grandis* (Table 1). Similar trends were observed in the below-ground biomass and carbon stock of the forest reserve.

The total mean above-ground carbon stock of trees and shrubs with DBH ≥ 5 cm, which was found to be 107.48 ± 61.28 Mg C ha^{-1} in this study, is lower than those reported in other tropical forests (Agboola et al. 2021; Mauya and Madundo 2021; Buragohain et al. 2023). For example, Mauya and Madundo (2021) observed carbon stocks in six lowland forest reserves in the East Usambara tropical mountain forests of Tanzania, with values ranging from 128.70±23.28 Mg C ha^{-1} (Kwamngumi) to 166.20 ± 37.18 Mg C ha^{-1} (Longuza). Agboola et al. (2021) reported carbon stocks ranging from 98.67 Mg C ha^{-1} to 555.95 Mg C ha^{-1} in six lowland forests in Nigeria, while Buragohain et al. (2023) reported carbon stocks of 142.74 Mg C ha^{-1} and 185.89 Mg C ha^{-1} from the Kakoi reserve forest in India.

The higher carbon stock values reported in these studies could be attributed to the presence of numerous large trees, which contribute significantly to the overall forest carbon density. In contrast, the lower value observed in this study may be due to the dominance of trees in lower diameter classes, leading to a lower contribution to the total carbon stock (Figure 4). Other factors such as the study area, stand characteristics, sampling methodology, level of disturbance, geographical variation, and temporal variation could also contribute to the observed variability in carbon stock results.

In conclusion, the results of this study indicate that RCFR has a high diversity of woody species (H'=2.91) but low species richness (29 species), particularly when compared to other lowland, riverine, and freshwater swamp forests in Tanzania and other tropical regions. Tree density and basal area in RCFR are also lower than those reported in other tropical forests. Similarly, the carbon stock in this study was lower than values found in other lowland and groundwater forests. Among the species, *S. siamea* (exotic) was the most overexploited, appearing in 16% of the plots.

The carbon stock estimates presented here provide valuable baseline data for monitoring changes in carbon storage within the forest. To sustain or enhance the biodiversity and management of RCFR in the future, we recommend that efforts to protect the forest be intensified. This should include monitoring the dominance and spread of exotic species and safeguarding the reserve from encroachment. Furthermore, assessing the regeneration patterns of local species under the canopy of both indigenous and exotic species is crucial to determine whether the presence of exotic species threatens the sustainability of native species in the reserve. Additionally, future studies should consider quantifying carbon stock in other carbon pools to provide a more comprehensive estimate of the total carbon stock in the forest.

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