

Stand structure, diversity, and carbon stock assessment of Lake Duluti Forest Reserve in Tanzania

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Abstract. *Mfinanga US, Mwakalukwa EE. 2025. Stand structure, diversity, and carbon stock assessment of Lake Duluti Forest Reserve in Tanzania. Nusantara Bioscience 17: 185-193.* For a successful conservation of biodiversity in a particular forest, assessment of its status and underlying threats is important. Estimation of carbon stocks locked up in the forest is also key in designing the required climate change mitigation options. However, there is limited information on the biodiversity status and carbon storage potential of many forest reserves in Tanzania. This study assessed the tree and shrub species diversity, composition, stand structure, and carbon stock potential of the Lake Duluti Forest Reserve (LDFR). Data were collected from 40 systematically established concentric plots (0.071 ha each) covering a total forest area of 26.24 ha. A total of 48 tree and shrub species were recorded, comprising both adult individuals (DBH \geq 5 cm) and regenerants (DBH < 5 cm), representing 25 plant families. Adult individuals accounted for 42 species from 23 families, while regenerants included 22 species from 15 families. The Shannon-Wiener diversity index (H') was 3.21 for adults and 2.80 for regenerants, indicating high species diversity. The mean stem density of adult trees was 197 ± 97 stems ha^{-1} , with a basal area of 16.27 ± 7.30 m^2 ha^{-1} . The estimated above-ground carbon stock was 79.24 ± 35.31 Mg C ha^{-1} , while below-ground carbon stock was 30.86 ± 12.77 Mg C ha^{-1} . The absence of visible anthropogenic disturbance suggests effective conservation measures are in place. These findings highlight the ecological stability and carbon sequestration potential of LDFR and highlight the need for strategic planning to enhance biodiversity conservation and carbon stock management.

Keywords: Catchment forests, climate change, eco-tourism, vegetation composition, volcanic lakes

INTRODUCTION

Tanzania is globally recognized for its exceptional biodiversity, iconic tourist attractions, and significant role in global conservation efforts (URT 2021a). The country's protected areas, under central government jurisdiction, cover approximately 307,800 km^2 —equivalent to 32.5% of the total land area (NAFORMA 2015; URT 2021a). These areas include 21 National Parks, 29 Game Reserves, 23 Game Controlled Areas, the Ngorongoro Conservation Area, 22 Nature Forest Reserves, various other forest reserves, and marine parks and reserves (URT 2015; NAFORMA 2015; URT 2021a). Additionally, about 1.4 million hectares of gazetted catchment forests contribute to the network of protected landscapes (NAFORMA 2015).

These protected areas are crucial not only for biodiversity conservation and climate change mitigation but also as key revenue generators through tourism. Tourism contributes approximately 17% to Tanzania's national GDP and accounts for 25% of total export earnings, making it a cornerstone of the national economy (URT 2021a). Serengeti National Park, for example, generates over 53% of Tanzania National Parks revenue and is globally known for the Great Migration. However, the revenue potential of other protected areas remains underexplored.

In 2022, the Tanzania Forest Services Agency (TFS) reported increased tourist visits to the country's nature forest reserves, collecting approximately USD 550,000 from

242,824 visitors (Ract et al. 2024). This highlights growing interest in eco-tourism beyond traditional wildlife safaris. Nevertheless, limited awareness of the biodiversity and attractions within forest reserves continues to constrain revenue generation from these sites. The availability of ecological and biodiversity information is therefore critical to promoting eco-tourism and attracting a broader spectrum of visitors (URT 1998; URT 2021b).

Lake Duluti Forest Reserve (LDFR), located in the Arumeru District of the Arusha Region, is one such underutilized catchment forest reserve (Iddi 1998; NAFORMA 2015). The reserve, notable for its ecological, hydrological, and cultural significance, contains a central volcanic lake that serves as a key tourist attraction. It also supports a variety of ecologically important flora and fauna (TFS 2022). However, no previous study has documented the plant species composition or carbon storage potential of LDFR. The absence of such information may have contributed to its lower profile among tourist destinations in northern Tanzania, consequently limiting the revenue potential for TFS, the agency responsible for its management.

This study was conducted to assess the forest condition and carbon storage potential of the Lake Duluti Forest Reserve. The findings aim to fill critical knowledge gaps and enhance public awareness of the ecological functions of tropical moist forests, particularly their role in climate change mitigation. Specifically, the study aimed to: (i) assess tree and shrub species diversity and composition in

LDFR; (ii) determine the stand structure (stem density, basal area, and diameter distribution) of tree and shrub species; (iii) evaluate the regeneration status of tree and shrub species; and (iv) estimate the above- and below-ground carbon stocks within LDFR.

MATERIALS AND METHODS

Study area

Lake Duluti Forest Reserve (LDFR) is a protected catchment forest managed by the Tanzania Forest Services Agency (TFS) under the Ministry of Natural Resources and Tourism (TFS 2022). The reserve is located in Akheri Ward, Arumeru District, approximately 14 km from Arusha City, at coordinates 3°23'S and 36°47'E and an elevation of 1,290 meters above sea level (Lovett and Pócs 1993; TFS 2022) (Figure 1). The site is accessible via a 1.3 km road from Tengeru Township off the Arusha-Moshi highway. LDFR was initially gazetted under Government Notice No. 314 on 2 July 1965. Following a resurvey in 2017, the reserve boundaries were revised and officially updated in Government Notice No. 694 of 28 August 2020 (Map JB No. 2774) to incorporate previously excluded forest areas (TFS 2022). The total area of the reserve, including the lake, is approximately 86.24 ha. Lake Duluti occupies about 60 ha, while the surrounding forest spans approximately 26.24 ha (Lovett and Pócs 1993). The lake, a volcanic crater, has an estimated depth of 700 meters. Despite its volcanic origin, the water is non-saline, suggesting that rainfall is the primary source of recharge. It remains full throughout the year, sustained by underground springs, with no visible surface inflows or outflows.

The local climate is characterized by oceanic rainfall and continental temperatures, with an annual average precipitation of approximately 1,100 mm. Mean monthly maximum temperatures reach 21°C in March, and minimum temperatures drop to about 17°C in July (Lovett and Pócs 1993). The forest structure is largely influenced by groundwater availability. Submontane forest thrives in areas 5-10 m above the lake level and 20-50 m from the shore, where groundwater is abundant. On the upper slopes, where groundwater is limited, dry montane forest dominates. Additionally, a floating island of *Cyperus papyrus* L. has formed along the lake's northern shoreline (Lovett and Pócs 1993). The reserve serves as a vital water source for the Tengeru settlement, the Agricultural Training Institute, and adjacent coffee farms through a water plant situated on the eastern lake edge. LDFR also holds significant recreational value, attracting eco-tourism activities such as canoeing and sport fishing. The forest reserve supports a variety of wildlife, including small mammals like the vervet monkey (*Cercopithecus aethiops* subsp. *pygerythrus*), blue monkey (*Cercopithecus neumanni*), black-and-white colobus (*Colobus guereza* Rüppell, 1835), and marsh mongoose (*Ichneumia albicauda* (G.Cuvier, 1829)). LDFR also provides an important breeding habitat for birds. Common avian species observed include the white-faced whistling duck (*Dendrocygna viduata* (Linnaeus, 1766)), chestnut weaver (*Ploceus rubiginosus* Rüppell, 1840), bronze mannikin (*Lonchura cucullata* (Swainson, 1837)), and little swift (*Apus affinis* (J.E.Gray, 1830)).

LDFR is bordered by Patandi Village, which has an estimated population of 6,070. The local economy primarily depends on agriculture and livestock keeping, although some residents are also engaged in cultural eco-tourism and the sale of forest products such as honey harvested from homesteads (TFS 2022).

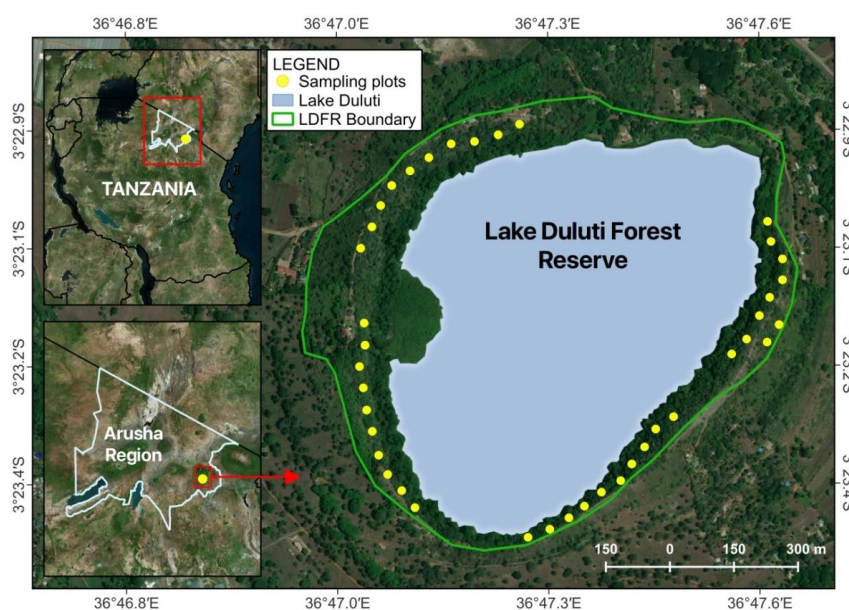


Figure 1. Map of Arusha region, Tanzania, showing the location of the Lake Duluti Forest Reserve (RDFR) and the layout of sample plots in the reserve (filled yellow circles)

Data collection

A systematic sampling design was employed for ecological data collection. Forty circular sample plots, each with a 15 m radius, were established at intervals of 50 m both within and between transect encircling the lake. In each plot, vegetation data were collected using concentric subplots of different radii, based on Diameter at Breast Height (DBH) classes: Within a 2 m radius: all regenerants with DBH < 5 cm were identified, counted, and recorded; within a 5 m radius: all trees and shrubs with DBH ≥ 5 cm and < 10 cm were measured, identified, and recorded; within a 10 m radius: all individuals with DBH ≥ 10 cm and < 20 cm were recorded similarly; within a 15 m radius: all trees and shrubs with DBH ≥ 20 cm were measured and recorded. Plot coordinates and elevations were recorded using a handheld GPS device.

Data analysis

The collected data were analyzed for species richness, composition, diversity, stem density, basal area, and estimation of above- and below-ground biomass and carbon stocks. Species richness was determined by compiling a comprehensive list of plant species across all sample plots. Species diversity was calculated using the Shannon-Wiener diversity index ($H' = -\sum p_i \ln p_i$), where p_i is the proportion individuals belonging to the i^{th} species (Kent 2012). The species Importance Values Index (IVI) was calculated as the sum of the relative frequency, relative density, and relative basal area (Kent and Coker 1992). Stem density (number of stems per hectare) was calculated using the formula: $N = (n/a_i)$, where n is the number of individuals in a plot, and a_i is the area of plot (ha). Basal area ($m^2 ha^{-1}$) was calculated from the DBH measurement using the formula: $G = (G_i/n)$, where G_i is the basal area of a plot ($m^2 ha^{-1}$), and n = number of sample plots.

The allometric models developed by Masota et al. (2016) for lowland and humid montane forests were employed to estimate both above-ground and below-ground biomass of the forest. Subsequently, the biomass values were converted into carbon stock per hectare by applying a carbon conversion factor of 0.49, as recommended by Manyanda et al. (2020). The resulting carbon stocks were expressed in megagrams of carbon per hectare ($Mg C ha^{-1}$).

The following equations were applied for biomass estimation:

Total tree above-ground biomass (kg) = $0.9635 \times DBH^{1.9440}$ ($n = 60$, RMSE (kg) = 1020.3, $R^2 = 0.80$, MPE (%) = 0.0).

Total tree below-ground biomass (kg) = $7.5811 \times DBH^{1.16801}$ ($n = 29$, RMSE (kg) = 312.7, $R^2=0.71$, MPE (%) = 2.0).

Where DBH refers to the diameter at breast height (cm), RMSE denotes the root mean square error, R^2 indicates the coefficient of determination and MPE represents the mean percentage error.

RESULTS AND DISCUSSION

Species richness and composition

A total of 48 tree and shrub species of both adults (≥ 5 cm Dbh) and regenerants (< 5 cm Dbh) belonging to 25 plant families and 41 genera were identified and recorded in the forest (Tables 1 and 2). Trees contributed the most to the identified species (83%), while shrubs contributed the least (17%). Tree species accounted for the majority of observations (83%), whereas shrubs contributed only 17%. The most represented plant families were Fabaceae and Moraceae, each with five species. These were followed by Euphorbiaceae, Meliaceae, Rubiaceae, and Rutaceae, which each comprised three species. The remaining families generally contained one or two species.

For adult individuals (DBH ≥ 5 cm), a total of 290 trees were measured, with diameters ranging from 5 to 160 cm. These individuals represented 42 species across 23 families and 36 genera (Table 1). As with the total count, tree species dominated (83%), while shrubs remained a minority (17%). Fabaceae and Moraceae remained the most prevalent families, each with five species. Additional common families among adults included Anacardiaceae, Euphorbiaceae, Meliaceae, and Rutaceae, each represented by three species (Table 1). The three most ecologically dominant adult species, based on the Importance Value Index (IVI), were *Bridelia micrantha* (Hochst.) Baill. (42.5%), *Ficus sycomorus* L. (34.4%), and *Sorindeia madagascariensis* (Spreng.) DC. (22.8%) (Table 1). In contrast, the least represented species in the reserve were *Cedrela odorata* L. (0.9%), *Garcinia* sp. (0.9%), and *Obetia radula* (Baker) B.D.Jacks. (0.7%). On average, five species were recorded per sampling plot, with species richness per plot ranging from 2 to 8. The species accumulation curve (Figure 2) reached an asymptote, suggesting that the sampling effort was adequate to capture the majority of tree and shrub species present in the forest.

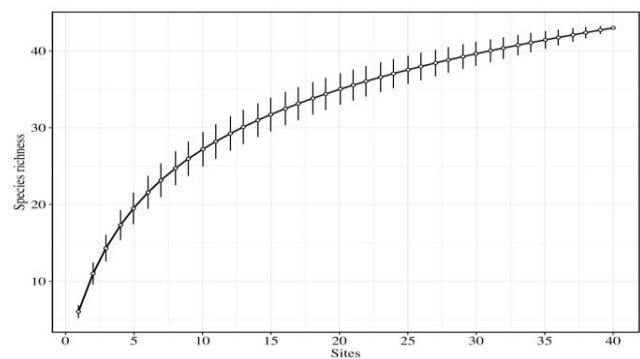


Figure 2. Species accumulation curve of tree species in the Lake Duluti Forest Reserve, Arumeru District in Tanzania. The curve depicts the expected number of species as a function of the sampled area, with the upper and lower bounds representing the 95% confidence intervals

Table 1. Checklist of adult tree and shrub species with Dbh \geq 5 cm sorted by IVI identified in the Lake Duluti Forest Reserve, Arumeru district, Tanzania

Botanical name	Family	Habit	Freq. (%)	*H'	Rf (%)	RDe (%)	RDo (%)	IVI	Density (stems ha ⁻¹)	Basal area (m ² ha ⁻¹)	AGC (Mg C ha ⁻¹)	BGC (Mg C ha ⁻¹)
<i>Bridelia micrantha</i> (Hochst.) Baill.	Phyllanthaceae	Tree	65	0.28	12.9	12.8	16.7	42.5	19±4	1.91±0.42	9.43±2.05	3.95±0.70
<i>Ficus sycomorus</i> L.	Moraceae	Tree	40	0.20	8.0	6.0	20.5	34.4	8±2	4.83±1.24	22.85±5.84	5.12±1.19
<i>Sorindeia madagascariensis</i> DC.	Anacardiaceae	Tree	40	0.21	8.0	8.4	6.4	22.8	16±7	1.31±0.71	6.44±3.44	2.68±1.11
<i>Newtonia buchananii</i> (Baker) G.C.C.Gilbert & Boutique	Fabaceae	Tree	27.5	0.13	5.5	6.8	6.3	18.5	9±3	0.88±0.52	4.21±2.45	1.37±0.50
<i>Drypetes gerrardii</i> Hutch.	Putranjivaceae	Tree	30	0.18	6.0	7.4	3.1	16.5	19±8	0.42±0.14	2.16±0.71	1.67±0.60
<i>Trichilia emetica</i> (Forssk.) Vahl	Meliaceae	Tree	30	0.16	6.0	4.8	4.3	15.0	7±2	0.78±0.33	3.81±1.61	1.52±0.51
<i>Albizia gummifera</i> (J.F.Gmel.) C.A.Sm.	Fabaceae	Tree	27.5	0.16	5.5	3.6	4.0	13.1	7±2	0.71±0.26	3.43±1.27	1.50±0.53
<i>Turraea robusta</i> Gürke	Meliaceae	Shrub	20	0.13	4.0	5.0	2.8	11.8	7±3	0.23±0.10	1.18±0.51	0.82±0.32
<i>Deinbollia kilimandscharica</i> Taub.	Sapindaceae	Shrub	15	0.11	3.0	4.3	2.2	9.5	11±6	0.21±0.09	1.08±0.48	0.82±0.34
<i>Allophylus africanus</i> P.Beauv.	Sapindaceae	Shrub	15	0.10	3.0	4.5	1.9	9.3	12±7	0.22±0.11	1.23±0.54	0.94±0.39
<i>Psychotria capensis</i> subsp. <i>riparia</i> (K.Schum. & K.Krause) Verdc.	Rubiaceae	Shrub	12.5	0.09	2.5	5.5	1.2	9.1	15±7	0.08±0.04	0.43±0.20	0.66±0.30
<i>Croton megalocarpus</i> Hutch.	Euphorbiaceae	Tree	15	0.15	3.0	3.4	2.5	8.9	10±5	0.31±0.12	1.58±0.63	1.09±0.45
<i>Ficus sur</i> Forssk.	Moraceae	Tree	12.5	0.07	2.5	2.3	3.0	7.7	2±1	0.50±0.29	2.41±1.39	0.73±0.36
<i>Albizia petersiana</i> (Bolle) Oliv.	Fabaceae	Tree	7.5	0.12	1.5	2.6	3.4	7.5	5±3	0.45±0.30	2.24±1.48	1.05±0.68
<i>Trilepisium madagascariense</i> DC.	Moraceae	Tree	12.5	0.09	2.5	3.4	1.6	7.5	9±7	0.14±0.07	0.73±0.35	0.56±0.25
<i>Cordia africana</i> Lam.	Boraginaceae	Tree	12.5	0.08	2.5	0.9	2.3	5.7	2±1	0.89±0.64	4.19±2.99	0.98±0.54
<i>Rauvolfia caffra</i> Sond.	Apocynaceae	Tree	12.5	0.08	2.5	1.2	1.7	5.4	2±1	0.23±0.11	1.17±0.53	0.54±0.23
<i>Cussonia holstii</i> Harms ex Engl.	Araliaceae	Tree	7.5	0.06	1.5	1.9	1.7	5.0	3±2	0.09±0.06	0.46±0.32	0.31±0.19
<i>Strychnos</i> sp.	Loganiaceae	Tree	10	0.10	2.0	2.2	0.5	4.7	8±5	0.07±0.04	0.38±0.20	0.45±0.23
<i>Ficus lutea</i> Vahl	Moraceae	Tree	7.5	0.05	1.5	0.8	2.1	4.4	1±1	0.21±0.13	1.05±0.66	0.38±0.23
<i>Spathodea campanulata</i> P.Beauv.	Bignoniaceae	Tree	5	0.05	1.0	0.8	2.0	3.7	1±1	0.37±0.28	1.80±1.33	0.52±0.36
<i>Dombeya rotundifolia</i> (Hochst.) Planch.	Malvaceae	Tree	7.5	0.05	1.5	0.9	1.0	3.4	2±1	0.08±0.05	0.41±0.23	0.25±0.14
<i>Ozoroa insignis</i> Delile	Anacardiaceae	Tree	5	0.05	1.0	1.1	1.2	3.3	2±1	0.11±0.10	0.56±0.49	0.28±0.23
<i>Vangueria infausta</i> Burch.	Rubiaceae	Shrub	7.5	0.05	1.5	1.0	0.8	3.3	2±1	0.04±0.02	0.21±0.13	0.19±0.11
<i>Tabernaemontana ventricosa</i> Hochst. ex A.DC.	Apocynaceae	Tree	7.5	0.05	1.5	1.1	0.3	2.9	2±1	0.04±0.02	0.20±0.12	0.20±0.11
<i>Sarcomelicope simplicifolia</i> (Endl.) T.G.Hartley	Rutaceae	Tree	5	0.03	1.0	1.4	0.3	2.7	4±3	0.04±0.03	0.22±0.15	0.25±0.18
<i>Combretum molle</i> R.Br. ex G.Don	Combretaceae	Tree	5	0.05	1.0	0.7	0.8	2.6	1±1	0.06±0.04	0.32±0.23	0.19±0.14
<i>Celtis africana</i> Burm.f.	Cannabaceae	Tree	5	0.03	1.0	0.4	0.9	2.3	1±0	0.08±0.06	0.38±0.32	0.17±0.13
<i>Albizia chinensis</i> (Osbeck) Merr.	Fabaceae	Tree	2.5	0.03	0.5	0.6	0.9	2.0	1±1	0.09±0.09	0.45±0.45	0.20±0.20
<i>Manilkara</i> sp.	Sapotaceae	Tree	2.5	0.02	0.5	0.2	0.8	1.5	0±0	0.08±0.08	0.37±0.37	0.14±0.14
<i>Senna siamea</i> (Lam.) H.S.Irwin & Barneby	Fabaceae	Tree	2.5	0.03	0.5	0.5	0.4	1.4	2±2	0.02±0.02	0.11±0.11	0.12±0.12
<i>Commiphora eminii</i> Engl.	Burseraceae	Tree	2.5	0.02	0.5	0.3	0.5	1.3	0±0	0.08±0.08	0.41±0.41	0.14±0.14
<i>Rhus natalensis</i> Bernh.	Anacardiaceae	Shrub	2.5	0.02	0.5	0.6	0.2	1.3	3±3	0.02±0.02	0.13±0.13	0.17±0.17
<i>Ficus thonningii</i> Blume	Moraceae	Tree	2.5	0.02	0.5	0.1	0.6	1.2	0±0	0.54±0.54	2.53±2.53	0.43±0.43
<i>Calodendrum capense</i> (L.f.) Thunb.	Rutaceae	Tree	2.5	0.02	0.5	0.5	0.1	1.1	1±1	0.01±0.01	0.04±0.04	0.05±0.05
<i>Clausena anisata</i> (Willd.) Hook.f.	Rutaceae	Shrub	2.5	0.02	0.5	0.4	0.1	1.0	1±1	0.01±0.01	0.05±0.05	0.05±0.05
<i>Croton sylvaticus</i> Hochst.	Euphorbiaceae	Tree	2.5	0.02	0.5	0.4	0.1	1.0	0±0	0.03±0.03	0.15±0.15	0.08±0.08
<i>Euphorbia candelabrum</i> Welw.	Euphorbiaceae	Tree	2.5	0.02	0.5	0.3	0.2	1.0	1±1	0.01±0.01	0.07±0.07	0.07±0.07
<i>Trema orientale</i> (L.) Blume	Ulmaceae	Tree	2.5	0.02	0.5	0.5	0.0	1.0	1±1	0.01±0.01	0.03±0.03	0.04±0.04
<i>Cedrela odorata</i> Ruiz & Pav.	Meliaceae	Tree	2.5	0.02	0.5	0.2	0.2	0.9	0±0	0.01±0.01	0.06±0.06	0.04±0.04
<i>Garcinia</i> sp.	Clusiaceae	Tree	2.5	0.02	0.5	0.1	0.3	0.9	0±0	0.03±0.03	0.15±0.15	0.08±0.08
<i>Obetia radula</i> (Baker) Baker ex B.D.Jacks.	Urticaceae	Tree	2.5	0.02	0.5	0.2	0.0	0.7	1±1	0.02±0.02	0.11±0.11	0.09±0.09
Total			502.5	3.21	100	100	100	300	197 ± 97	16.27 ± 7.30	79.17 ± 35.31	30.86 ± 12.77

Note: * H' : Shannon-Wiener diversity index, Rf : Relative frequency, RDe: Relative density, RDo: Relative dominance (basal area), IVI : Importance Value Index, AGC : Above Ground Carbon (mean ± SE), BGC: Below Ground Carbon (mean ± SE), Plot size: 15 m radius. SE: Standard error

The 42 species belonging to 23 plant families recorded in this study from 40 concentric sample plots represent a lower species richness than those reported by several comparable studies. For example, Mwakalukwa et al. (2023a) recorded 54 species from 29 families using 23 plots of 0.071 hectares in the dry evergreen montane forest of the Essimngor Nature Forest Reserve in Tanzania. Similarly, Sitati et al. (2014) reported 75 species from 100 plots of 0.02 hectares in the Gelai Forest Reserve, also in Tanzania. Daba et al. (2022) documented 68 species across 33 families using 100 plots of 0.04 hectares in the Afromontane Forest of Southwest Ethiopia. Furthermore, Noumi (2015) reported 146 species from 41 families using 60 plots of 0.1 hectares in Cameroon. In contrast, the current study's species richness exceeds that reported by Teshager et al. (2018), who identified 32 species from 20 families using 40 plots of 0.02 hectares in the Weiramba Forest, Ethiopia. The relatively lower species count in the present study may be attributed to differences in sampling intensity, including total area surveyed, number of plots, and plot sizes, which were generally higher in the aforementioned studies.

Species diversity

The Shannon-Wiener diversity index (H') for tree and shrub species with diameter at breast height equal to or greater than five centimeters in the LDFR was calculated as 3.21 (Table 1). The species contributing most to this diversity index were *B. micrantha* (0.28), *S. madagascariensis* (0.21), and *F. sycomorus* (0.20). This H' value is lower than those reported by Kacholi et al. (2015) in the moist forest of Uluguru Nature Forest Reserve, Tanzania ($H' = 4.03$), Mwaluseke et al. (2023) from the dry evergreen forest of Lendikinya Forest Reserve, Tanzania ($H' = 3.46$), and Noumi (2015) in Cameroon ($H' = 4.96$). However, it is higher than those documented in other studies. For example, Teshager et al. (2018) reported an H' of 2.3 in a moist forest in

Ethiopia, Mwakalukwa et al. (2023a) reported an H' of 2.7 in the Essimngor Nature Forest Reserve, Sitati et al. (2014) recorded an H' of 2.8 in the Gelai Forest Reserve, and Mwakalukwa and Masisi (2024) found an H' of 2.91 in the Rau Catchment Forest Reserve, a lowland groundwater forest in Tanzania.

According to Magurran (2004) and Noumi (2015), Shannon-Wiener index values typically range from 1.5 to 4.9 and rarely exceed 5. Ecosystems with values above 2 are generally considered to have moderate to high diversity. Therefore, the H' value of 3.21 in this study indicates that the LDFR supports a high level of species diversity among its tree and shrub populations. This relatively high diversity may be attributed to the low levels of disturbance observed in the forest.

Stand structure

The stem density and basal area for adult trees and shrubs with diameter at breast height equal to or greater than five centimeters in the LDFR were 197 ± 97 stems per hectare and 16.27 ± 7.30 square meters per hectare, respectively (Table 1). The species contributing most to stem density included *Drypetes gerrardii* Hutch. (19 ± 8 stems per hectare), *B. micrantha* (19 ± 4 stems per hectare), *S. madagascariensis* (16 ± 7 stems per hectare), and *Psychotria riparia* (15 ± 7 stems per hectare). Regarding basal area, *F. sycomorus* was the most dominant species, contributing 4.83 ± 1.24 square meters per hectare, followed by *B. micrantha* with 1.91 ± 0.42 square meters per hectare and *S. madagascariensis* with 1.31 ± 0.71 square meters per hectare. The stem density distribution by size class exhibited a reverse J-shaped pattern (Figure 3), which is characteristic of healthy regenerating forests. In contrast, the basal area distribution followed a normal J-shaped curve, with trees exceeding 70.1 centimeters in diameter contributing the most to the mean basal area of the forest (Figure 4).

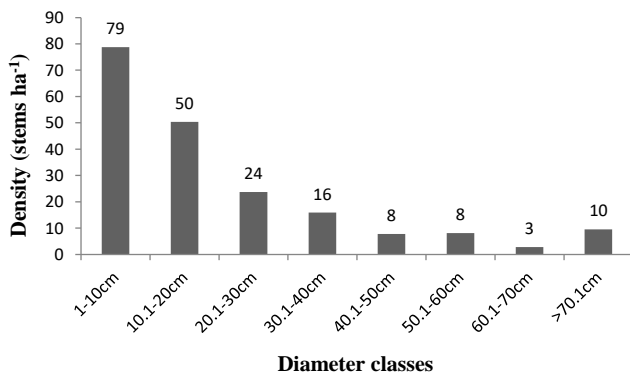


Figure 3. Distribution of density

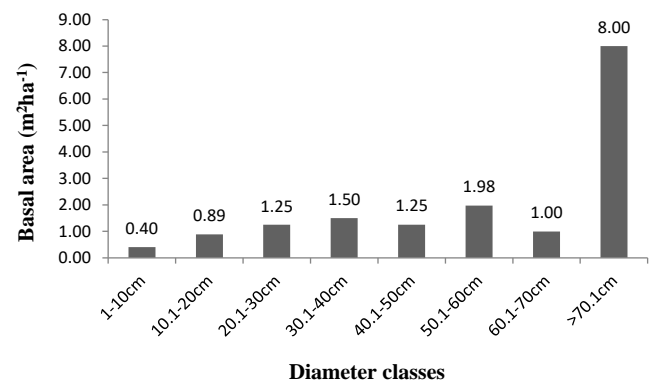


Figure 4. Distribution of basal area per hectare for trees and shrubs with ≥ 5 cm Dbh by diameter classes in Lake Duluti Forest Reserve, Arumeru District, Tanzania ($n = 40$)

The total mean stem density of adult individuals (dbh \geq 5 cm) recorded in this study was 197 ± 97 stems ha^{-1} , which is considerably lower than values reported from other forest reserves in East Africa. For instance, Mwakalukwa et al. (2023a) reported 288 ± 173 stems ha^{-1} in Essimingor Nature Forest Reserve, while Sitati et al. (2014) and Sitati et al. (2016) recorded 377 stems ha^{-1} and 435 stems ha^{-1} in Gelai and Ketumbeine Forest Reserves, respectively. Similarly, Kacholi et al. (2015) documented 390 stems ha^{-1} in the Uluguru Nature Forest Reserve, and Gebeyehu et al. (2019) reported stem densities ranging from 365.6 to 664.1 stems ha^{-1} , with a mean of 636.5 stems ha^{-1} across five Ethiopian forests. In western Cameroon, Noumi (2015) found a mean stem density of 544 stems ha^{-1} . Conversely, the stem density in this study exceeded the values reported by Mwakalukwa et al. (2023b) (190 ± 117 stems ha^{-1}) from the Lolkisale Village Land Forest Reserve and by Mwakalukwa and Masisi (2024), who recorded 185 ± 81 stems ha^{-1} in the lowland groundwater forest of Rau Catchment Forest Reserve. The relatively lower stem density observed in Lake Duruti Forest Reserve (LDFR) suggests that it is among the few moist, submontane, dry evergreen forests in Tanzania with lower stocking rates. This might be attributed to site-specific factors such as extensive water cover, which potentially limits the availability of terrestrial habitat for tree establishment. In contrast, higher stem densities in other forests could be linked to microclimatic conditions that enhance species establishment and survival.

With respect to basal area, the mean value recorded in LDFR was 16.27 ± 7.30 m^2 ha^{-1} for adult individuals (dbh \geq 5 cm). This is higher than the 11.47 ± 7.23 m^2 ha^{-1} reported by Mwakalukwa et al. (2023a) for Essimingor, 7.68 ± 5.17 m^2 ha^{-1} reported by Mwakalukwa et al. (2023b) for Lolkisale, and 11.42 ± 5.41 m^2 ha^{-1} reported for

Lendikinya Forest Reserve (Mwaluseke et al. 2023). However, it remains lower than the 23.05 ± 12.37 m^2 ha^{-1} observed by Mwakalukwa and Masisi (2024) in Rau Catchment Forest Reserve, 24 m^2 ha^{-1} reported by Kacholi et al. (2015) for Uluguru Nature Forest Reserve, and 26.87 m^2 ha^{-1} reported by Sitati et al. (2014) for Gelai Forest Reserve. Furthermore, Sitati et al. (2016) reported 30.49 ± 2.3 m^2 ha^{-1} from Ketumbeine, while higher values were recorded by Teshager et al. (2018) (32.10 m^2 ha^{-1}), Noumi (2015) (52.72 m^2 ha^{-1}), Mialla (2002) (69.3 ± 1.6 m^2 ha^{-1}), and Tynsong et al. (2022), who documented a mean of 61.72 ± 4.82 m^2 ha^{-1} in tropical evergreen forests of India. The relatively low stem density in LDFR likely accounts for its moderate basal area. In other studies, higher basal areas may be attributed to greater stem densities and the presence of more individuals in higher dbh classes, which substantially contribute to overall basal area values.

Regeneration

Regeneration status of tree and shrub species (dbh < 5 cm) in LDFR is summarized in Table 2. A total of 22 species representing 15 plant families and 20 genera were recorded. Of these, tree species constituted 77%, while shrub species accounted for 23%. The most dominant families were Fabaceae and Rubiaceae, each represented by three species. Ebenaceae, Loganiaceae, and Rutaceae followed, each with two species. The remaining families contributed one species each. The most frequently encountered regenerants were *D. gerrardii* (35%), *Newtonia buchananii* (Baker) G.C.C. Gilbert & Boutique (20%), *Psychotria capensis* subsp. *riparia* (K.Schum. & K.Krause) Verdc. (20%), and *Celtis africana* Burm.fil. (20%), which also significantly contributed to the Shannon-Wiener diversity index (H') and stem density values.

Table 2. Checklist of tree and shrub species of regenerants with DBH of < 5 cm sorted by density identified in Lake Duluti Forest Reserve, Arumeru District, Tanzania

Botanical name	Family	Habit	Frequency (%)	*H'	Density (stems ha^{-1})
<i>Drypetes gerrardii</i> Hutch.	Putranjivaceae	Tree	35	0.29	855±223
<i>Newtonia buchananii</i> (Baker) G.C.C. Gilbert & Boutique	Fabaceae	Tree	20	0.21	537±269
<i>Albizia gummifera</i> (J.F.Gmel.) C.A.Sm.	Fabaceae	Tree	17.5	0.19	418±185
<i>Sorindeia madagascariensis</i> (Spreng.) DC.	Anacardiaceae	Tree	17.5	0.19	279±132
<i>Sarcomelicope simplicifolia</i> (Endl.) T.G.Hartley	Rutaceae	Tree	15	0.17	279±123
<i>Psychotria capensis</i> subsp. <i>riparia</i> (K. Schum. & K. Krause) Verdc.	Rubiaceae	Shrub	20	0.21	259±100
<i>Strychnos mitis</i> S.Moore	Loganiaceae	Tree	2.5	0.05	199±199
<i>Celtis africana</i> Burm.fil.	Cannabaceae	Tree	20	0.21	199±68
<i>Clausena anisata</i> (Willd.) Hook.fil.	Rutaceae	Shrub	10	0.13	159±86
<i>Trichilia emetica</i> (Forssk.) Vahl	Meliaceae	Tree	12.5	0.15	159±71
<i>Albizia petersiana</i> (Bolle) Oliv.	Fabaceae	Tree	5	0.08	139±98
<i>Tabernaemontana ventricosa</i> Hochst. ex A.DC.	Apocynaceae	Tree	12.5	0.15	139±63
<i>Diospyros abyssinica</i> (Hiern) F.White	Ebenaceae	Tree	5	0.08	99±82
<i>Strychnos</i> sp.	Loganiaceae	Tree	7.5	0.11	80±48
<i>Vangueria infausta</i> Burch.	Rubiaceae	Shrub	7.5	0.11	80±48
<i>Deinbollia kilimandscharica</i> Taub.	Sapindaceae	Shrub	5	0.08	40±28
<i>Euclea divinorum</i> Hiern	Ebenaceae	Tree	5	0.08	40±28
<i>Flacourtia indica</i> (Burm.fil.) Merr.	Flacourtiaceae	Tree	5	0.08	40±28
<i>Trilepisium madagascariense</i> DC.	Moraceae	Tree	5	0.08	40±28
<i>Antidesma</i> sp.	Phyllanthaceae	Tree	2.5	0.05	20±20
<i>Commiphora eminii</i> Engl.	Bursaraceae	Tree	2.5	0.05	20±20
<i>Rothmannia</i> sp.	Rubiaceae	Shrub	2.5	0.05	20±20
Total			235	2.80	4,100 ± 1,967

Note: * Shannon-Wiener diversity index (H'), plot size = 2 m radius

The calculated Shannon-Wiener diversity index (H') for regenerants was 2.80, indicating high species diversity among young individuals in the reserve. The mean stem density of regenerants was $4,098 \pm 1,966$ stems ha^{-1} , which is notably higher than values reported in comparable forest ecosystems. For instance, Mwakalukwa et al. (2023a) reported 736 ± 621 stems ha^{-1} for regenerants ($dbh < 5$ cm) in Essimngor Nature Forest Reserve, while Teshager et al. (2018) recorded $1,635$ stems ha^{-1} for seedlings and $1,116$ stems ha^{-1} for saplings in Weiramba Forest, Ethiopia. These results suggest that despite the relatively low adult stem density, LDFR exhibits a high regeneration potential. The abundance of regenerants may reflect favorable microsite conditions, reduced anthropogenic disturbance, or successful reproductive strategies of dominant species, highlighting the ecological importance of LDFR as a viable forest system capable of sustaining long-term regeneration and resilience.

Biomass and carbon storage

The mean above-ground biomass and carbon stock potential of trees and shrubs with a Diameter at Breast Height (DBH) ≥ 5 cm in the Lake Duruti Forest Reserve (LDFR) were estimated at 158.48 ± 70.61 Mg ha^{-1} and 79.24 ± 35.31 Mg C ha^{-1} , respectively. Correspondingly, the mean below-ground biomass and carbon stock potential for the same category of individuals were 61.73 ± 25.54 Mg ha^{-1} and 30.86 ± 12.77 Mg C ha^{-1} (Table 1; Figure 5). Species contributing most significantly to above-ground carbon stocks were also those with the highest basal area, namely *F. sycomorus* (22.85 ± 5.84 Mg C ha^{-1}), *B. micrantha* (9.43 ± 2.05 Mg C ha^{-1}), and *S. madagascariensis* (6.44 ± 3.44 Mg C ha^{-1}). These same species were also dominant contributors to below-ground carbon stocks: *F. sycomorus* (5.12 ± 1.19 Mg C ha^{-1}), *B. micrantha* ($3.95 \pm$

0.70 Mg C ha^{-1}), and *S. madagascariensis* (2.68 ± 1.11 Mg C ha^{-1}) (Table 1). Biomass and carbon distribution across diameter classes revealed that individuals with DBH > 70.1 cm accounted for the largest share of the mean biomass and carbon stocks within the forest (Figure 5).

The total mean above-ground carbon stock (AGC) for trees and shrubs with DBH ≥ 5 cm in the Lake Duruti Forest Reserve (LDFR) was 79.24 ± 35.31 Mg C ha^{-1} . This value exceeds estimates reported from several other tropical forests. For instance, Swai et al. (2014) documented 48.4 ± 8.0 Mg C ha^{-1} from the Hanang Mountain Forest, while Shirima et al. (2015) recorded 54.30 ± 5.84 Mg C ha^{-1} from montane forests and miombo woodlands in Tanzania. Similarly, Mwakalukwa et al. (2023a) reported 56.93 ± 34.60 Mg C ha^{-1} in the dry evergreen forest of Essimngor Nature Forest Reserve, and Mwakalukwa et al. (2023b) found a much lower value of 19.55 ± 13.38 Mg C ha^{-1} in the Lolkisale Village Land Forest Reserve, North-East Tanzania. Mwaluseke et al. (2023) reported the lowest among these, with 16.04 ± 7.7 Mg C ha^{-1} from the Lendikinya Forest Reserve. In contrast, the AGC stock reported in this study is lower than some of the highest values recorded in other regions. Mwakalukwa and Masisi (2024) reported 107.48 ± 61.28 Mg C ha^{-1} from the lowland groundwater forest of Rau Catchment Forest Reserve in Tanzania. Even higher values have been reported from Ethiopia, including 180.18 ± 17.19 Mg C ha^{-1} and 106.71 ± 7.64 Mg C ha^{-1} in dry evergreen Afromontane forests (Asrat et al. 2022), and 191.6 ± 19.7 Mg C ha^{-1} across five Afromontane forests (Gebeyehu et al. 2019). Daba et al. (2022) reported 203.80 ± 12.38 Mg C ha^{-1} from a tropical forest in Southwest Ethiopia while, in India, Naveenkumar et al. (2017) recorded a range of 99–216 Mg C ha^{-1} from a tropical dry forest.

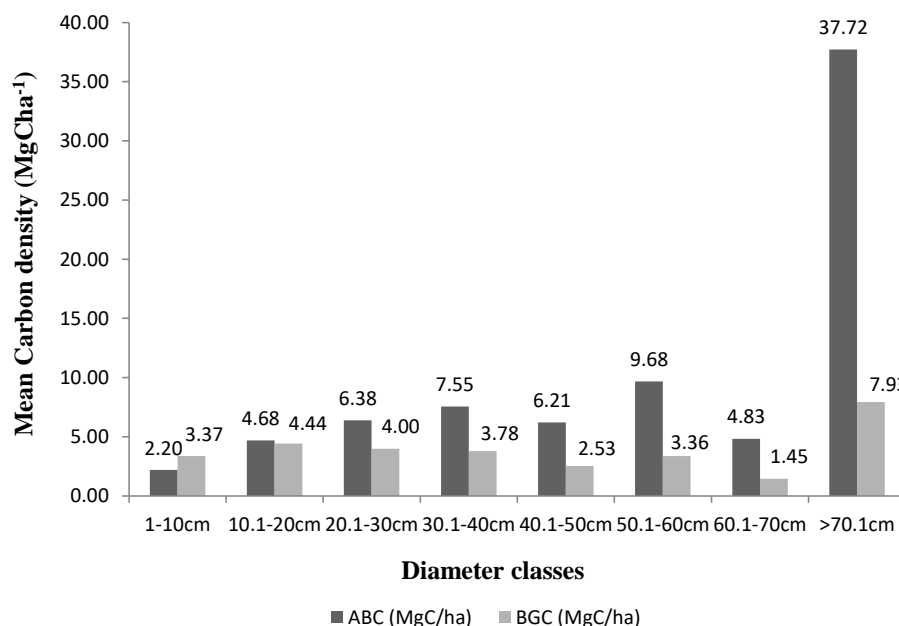


Figure 5. Distribution of both above and below-ground means carbon density for trees and shrubs with ≥ 5 cm DBH by diameter classes in the Lake Duluti Forest Reserve, Arumeru District, Tanzania ($n = 40$)

Regarding Below-Ground Carbon (BGC) density, the mean value of 30.86 ± 12.77 Mg C ha⁻¹ reported in this study falls within the range observed in comparable ecosystems. It is slightly lower than the 34.71 ± 19.72 Mg C ha⁻¹ reported by Mwakalukwa et al. (2023a) for the Essimngor Nature Forest Reserve. However, it is higher than values reported by Mwakalukwa and Masisi (2024), who documented 21.50 ± 12.26 Mg C ha⁻¹ for the Rau Catchment Forest Reserve, and significantly exceeds the 3.91 ± 2.68 Mg C ha⁻¹ recorded by Mwakalukwa et al. (2023b) for the Lolkisale Village Land Forest Reserve.

The variation in carbon stock values between studies can largely be attributed to differences in forest structure, particularly the size distribution of trees. Forests with many large trees generally exhibit higher biomass and carbon density. In contrast, a dominance of small trees tends to lower overall carbon stocks (Mauya and Madundo 2021). Other contributing factors include differences in terrain, climate, and methodological approaches—particularly the choice of allometric models used for biomass estimation.

Despite the relatively low stem density of adult trees (≥ 5 cm DBH), the LDFR stores considerable amounts of carbon in both above- and below-ground pools. The diameter of trees recorded ranged from 5 to 160 cm, with a notable proportion of large trees: 67% of the 290 trees measured had a DBH ≥ 20 cm, while 33% were < 20 cm. These findings highlight the ecological importance of large-diameter trees in carbon sequestration. To obtain a comprehensive estimate of total carbon storage, further quantification of additional carbon pools—such as soil, litter, deadwood, grasses, and herbs—is strongly recommended.

In conclusion, this study highlights the exceptional biodiversity and carbon storage potential of the Lake Duruti Forest Reserve. A total of 42 woody species were identified, and the species diversity index ($H' = 3.21$) suggests a floristically rich and heterogeneous ecosystem. Compared to other tropical forests, both in Tanzania and beyond, LDFR demonstrates relatively high above- and below-ground carbon stock values, largely driven by the presence of large trees. The high number of regenerants also reflects a healthy forest regeneration dynamic, indicative of long-term ecological stability. Together, the forest's structural composition, species richness, and significant carbon sequestration capacity highlight its conservation value.

To ensure the continued protection of this important ecosystem, the development and implementation of a comprehensive forest management plan is essential. Such a strategy would not only promote biodiversity conservation but also maintain and potentially enhance existing carbon stocks. This calls for immediate and coordinated conservation efforts involving local communities, stakeholders, and policymakers, to secure the long-term ecological and climate-regulating functions of LDFR.

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REFERENCES

- Asrat F, Soromessa T, Bekele T, Kurakalva RM, Guddeti SS, Smart DR, Steger K. 2022. Effects of environmental factors on carbon stocks of dry evergreen afromontane forests of the Choke Mountain Ecosystem, Northwestern Ethiopia. *Intl J For Res* 2022 (1): 9447946. DOI: 10.1155/2022/9447946.
- Daba DE, Dullo BW, Soromessa T. 2022. Effect of forest management on carbon stock of tropical moist afromontane forest. *Intl J For Res* 2022 (1): 3691638. DOI: 10.1155/2022/3691638.
- Gebeyehu G, Soromessa T, Bekele T, Teketay D. 2019. Carbon stocks and factors affecting their storage in dry afromontane forests of Awi Zone, North-western Ethiopia. *J Ecol Environ* 43: 7. DOI: 10.1186/s41610-019-0105-8.
- Iddi S. 1998. Eastern Arc Mountains and their national and global importance. *J East Afr Nat Hist* 87 (1): 19-26. DOI: 10.2982/00128317(1998)87[19:EAMATN]2.0.CO;2.
- Kacholi DS, Whitbread AM, Worbes M. 2015. Diversity, abundance, and structure of tree communities in the Uluguru forests in the Morogoro region, Tanzania. *J For Res* 26 (3): 557-569. DOI: 10.1007/s11676015-0078-0.
- Kent M, Coker P. 1992. *Vegetation Description and Analysis. A Practical Approach*. John Wiley and Sons, New York.
- Kent M. 2012. *Vegetation Description and Analysis, A Practical Approach, 2nd edition*. Wiley-Blackwell, John Wiley & Sons, Hoboken, NJ, USA.
- Lovett JC, Pocs T. 1993. *Assessment of the Condition of the Catchment Forest Reserves: A Botanical Appraisal*, Government Printers, Dar es Salaam.
- Magurran AE. 2004. *Measuring Biological Diversity*. Blackwell Publishing, Oxford.
- Manyanda BJ, Nzunda EF, Mugasha WA, Malimbwi RE. 2020. Estimates of volume and carbon stock removals in Miombo Woodlands of Mainland Tanzania. *Intl J For Res* 2020 (1): 4043965. DOI: 10.1155/2020/4043965.
- Masota AM, Bollandsås OM, Zahabu E, Eid T. 2016. Allometric Biomass and Volume Models for Lowland and Humid Montane Forests. In: Malimbwi RE, Eid T, Chamshama SAO (eds.). *Allometric Tree Biomass and Volume Models in Tanzania*. Department of Forest Mensuration and Management, Sokoine University of Agriculture, Tanzania.
- Mauya EW, Madundo S. 2021. Above-ground biomass and carbon stock of usambara tropical rainforests in Tanzania. *Tanz J For Nat Conserv* 90 (2): 63-82.
- Mialla YS. 2002. *Participatory Forest Resource Assessment and Zonation in Monduli Catchment Forest Reserve, Arusha, Tanzania [Dissertation]*. Sokoine University of Agriculture, Morogoro. [Tanzania]
- Mwakalukwa EE, Masisi B. 2024. Diversity, structure, and carbon storage of Rau catchment forest reserve in Moshi District, Tanzania. *Asian J For* 9 (1): 1-11. DOI: 10.13057/asianjfor/r090101.
- Mwakalukwa EE, Mwakisu A, Madundo S, Maliondo SMS. 2023b. Vegetation composition, diversity, stand structure, and carbon storage of Lolkisale Village Land Forest Reserve in the Northeastern part of Tanzania. *Nusantara Biosci* 15: 79-90. DOI: 10.13057/nusbiosci/n150109.
- Mwakalukwa EE, Mwakisu A, Maliondo SMS. 2023a. Woody species diversity, composition, structure and carbon storage of a dry evergreen montane forest of Essimngor Nature Forest Reserve in Tanzania. *Intl J Trop Drylands* 7 (1): 26-36. DOI: 10.13057/tropdrylands/t070104.
- Mwaluseke ML, Mwakalukwa EE, Maliondo SMS. 2023. Vegetation composition, diversity, stand structure and carbon stock of a dry

- evergreen montane forest of Lendikinya forest reserve in Tanzania. *Biodiversitas* 24 (1): 551-562. DOI: 10.13057/biodiv/d240164.
- NAFORMA. 2015. National Forest Resources Monitoring and Assessment of Tanzania Mainland. Ministry of Natural Resources and Tourism, Tanzania. Ministry for Foreign Affairs of Finland & Food and Agriculture Organisation of the United Nations.
- Naveenkumar J, Arunkumar KS, Sundarapandian SM. 2017. Biomass and carbon stocks of a tropical dry forest of the Javadi Hills, Eastern Ghats, India. *Carbon Manag* 8 (5-6): 351-361. DOI: 10.1080/17583004.2017.1362946.
- Noumi E. 2015. Floristic structure and diversity of a tropical sub-montane evergreen forest, in the Mbam Minkom Massif (Western Yaoundé). *J Biol Life Sci* 6 (1): 149-193. DOI: 10.5296/jbls.v6i1.7028.
- Ract C, Burgess ND, Dinesen L, Sumbi P, Malugu I, Latham J, Anderson L, Gereau RE, Gonçalves de Lima M, Akida A, Nashanda E, Shabani Z, Tango Y, Mteleka S, Santos Silayo D, Mwangi J, Lyatuu G, Platts PJ, Rovero F. 2024. Nature Forest Reserves in Tanzania and their importance for conservation. *PLoS ONE* 19 (2): e0281408. DOI: 10.1371/journal.pone.0281408.
- Shirima DD, Totland Ø, Munishi PKT, Moe SR. 2015. Relationships between tree species richness, evenness and above-ground carbon storage in montane forests and miombo woodlands of Tanzania. *Basic Appl Ecol* 16 (3): 239-249. DOI: 10.1016/j.baae.2014.11.008.
- Sitati N, Gichohi N, Lenaiyasa P, Maina M, Warinwa F, Muruthi P, Sumba DS, Mandima J. 2016. Tree species diversity and dominance in Ketumbeine Forest Reserve, Tanzania. *J Biodivers Manag For* 5: 3. DOI: 10.4172/2327 4417.1000161.
- Sitati N, Gichohi N, Lenaiyasa P, Millanga P, Maina M, Warinwa F, Muruthi P. 2014. Tree species diversity and dominance in Gelai Forest Reserve, Tanzania. *J Energy Nat Resour* 3 (3): 31-37. DOI: 10.11648/j.jenr.20140303.12.
- Swai G, Ndangalasi HJ, Munishi PKT, Shirima DD. 2014. Carbon stocks of Hanang forest, Tanzania: An implication for climate mitigation. *J Ecol Nat Environ* 6 (3): 90-98. DOI: 10.5897/JENE2013.0418.
- Teshager Z, Argaw M, Eshete A, Gebew Z. 2018. Woody species diversity, structure and regeneration status in Weiramba forest of Amhara region, Ethiopia: Implications of managing forests for biodiversity conservation. *J Nat Sci Res* 8 (5): 16-31.
- TFS (Tanzania Forest Services Agency). 2022. Five years management plan for lake Duluti forest reserve 2022/23 - 2026/27 (Draft). Ministry of Natural Resources and Tourism.
- Tynsong H, Dkhar M, Tiwari BK. 2022. Tree diversity and vegetation structure of the tropical evergreen forests of the southern slopes of Meghalaya, North East India. *Asian J For* 6 (1): 22-36. DOI: 10.13057/asianjfor/r060104.
- URT (United Republic of Tanzania). 1998. The National Forest Policy. Forestry and Beekeeping Division. Ministry of Natural Resource and Tourism. Dar es Salaam.
- URT (United Republic of Tanzania). 2015. National Biodiversity Strategy and Action Plan (NBSAP) 2015 2020. Vice President's Office, Division of Environment, United Republic of Tanzania, Dar es salaam.
- URT (United Republic of Tanzania). 2021a. The Budget Speech for the Ministry of Natural Resources and Tourism in the year 2022/2023. Minister for Natural Resources and Tourism. Dodoma.
- URT (United Republic of Tanzania). 2021b. National Forest Policy Implementation Strategy (2021-2031). United Republic of Tanzania. Ministry of Natural Resources and Tourism.