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ORIGINAL RESEARCH ARTICLE

Comparative Assessment of Aboveground Carbon Stock and Annualized Accumulation by Urban Weeping Fig (*Ficus Benjamina L.)* and Madagascar Almond (*Terminalia Mantaly H. Perrier*) Trees in Dutse, Northern Nigeria

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ABSTRACT

Urban trees contribute to climate-change mitigation by storing carbon in their biomass. The study compared the estimated aboveground carbon stock and the average annualized carbon accumulation of the Weeping fig (*Ficus benjamina L.*) and Madagascar almond (*Terminalia mantaly H. Perrier*) along Muhammad Saad Abubakar Street, Dutse in Jigawa State, Nigeria. The fieldwork was done in October – November 2021. Ten trees were selected from two even-aged (7 and 18 years) cohorts of *F. benjamina* and *T. mantaly* respectively using a purposive sampling design. Assessments of stand age were based on municipal planting records, stem circumference at 1.3 m, and total tree height (clinometer). Diameter at breast height (DBH) was derived from circumference. The aboveground green weight (GW) was estimated by diameter-class allometric equations, dry weight as 50% of GW, and carbon stock as 50% of dry weight. Annualized carbon accumulation was determined as carbon stock/cohort age. Mean aboveground carbon stock was 72.2 ± 34.1 kg C tree^{-1} for *F. benjamina* and 458.3 ± 138.2 kg C tree^{-1} for *T. mantaly.* Mean annualized accumulation was 10.12 ± 4.92 kg C year^{-1} for *F. benjamina* and 25.46 ± 7.65 kg C year-1 for *T. mantaly*. An independent-samples t-test showed a significant difference in annualized accumulation (t = 5.33, df = 18, p = 0.00004, mean difference = 15.34 kg C year^{-1}, 95% CI = 9.29–21.39, Cohen's d = 2.38). The results show that under the conditions studied the aboveground carbon stock and annualized accumulation of the sampled older *T. mantaly* cohort were higher than those of the sampled younger *F. benjamina* cohort. Both species can continue to be useful for shade, amenity, and urban greening purposes. Recommended carbon pools belowground and in the soil, age-matched replicated designs, and longitudinal growth measurements.

Keywords: Aboveground biomass, Carbon stock, Climate-change mitigation, *Ficus benjamina*, *Terminalia mantaly*, Urban forestry

Introduction

The concentration of atmospheric carbon dioxide (CO_2) has increased from about 280 parts per million (ppm) by volume in pre-industrial times to over 420 ppm by volume in recent years, primarily due to the burning of fossil fuels, cement production, and changes in land use (IPCC, 2023; Nunes, 2023). Climate change, global warming, climate variability, sea-level rise, and changes in ecosystem functioning are all closely linked to the enhanced greenhouse effect, which is a main contributor to the global warming of today's world. The Paris

Agreement and the United Nations Framework Convention on Climate Change focus on reducing emissions as well as increasing carbon sequestration potential. The conservation and expansion of tree cover, including urban and peri-urban forests, are among the most prominent NbS, as they help sequester carbon and offer co-benefits such as green roofs, green walls, and reduction of air pollution (Nowak *et al.,* 2013; Escobedo *et al.,* 2019; Pataki *et al.,* 2021).

Estimating aboveground biomass by allometric relationships between readily measured attributes such as diameter at breast height (DBH) and height are commonly used for quantifying carbon storage and sequestration at the individual-tree scale (Khan *et al.,* 2025; Bhebe *et al.,* 2024; Chave *et al.,* 2014; Conti *et al.,* 2019). In urban environments, non-destructive methods are generally preferred since felling is generally not acceptable. The carbon content is generally taken as about 50% of oven-dry woody biomass as is recommended for many broadleaf species by the IPCC (2006). Sequestration is sometimes approximated by dividing cumulative carbon storage by tree age, which provides an equivalent measure of sequestration for even-aged stands, but does not account for non-linear carbon storage over a tree's life (Walsh *et al.,* 2025; He *et al.,* 2021; Köhl *et al.,* 2017; Stephenson *et al.,* 2014).

Ficus benjamina L. Weeping fig (*Ficus benjamina, Moraceae*) is an evergreen tree that grows throughout tropical and Southeast Asian regions and is widely used as an ornamental or shade tree in tropical and subtropical urban environment (Rani *et al.,* 2025). Tolerant of pruning, compacted soils, and widely planted in urban situations in Nigeria. *Terminalia mantaly H*. Perrier (*Combretaceae*) is a medium sized street and park tree originating in Madagascar, widely used in East and West Africa, is drought tolerant once established, and has a layered crown. The comparative carbon performance of both species under local Sudan-savanna conditions has not been documented systematically, although both species are found along major corridors in the capital of Jigawa State, Dutse. Dutse is situated in a semi-arid region with a brief rainy season, a high evaporative demand, and desertification stresses on neighbouring landscapes. State and local governments have promoted afforestation and urban greening in recent years as environmental-management options, but there are no published local estimates to inform species selection for dual use (both desertification control and carbon mitigation). Comparative data of *F. benjamina* and *T. mantaly* would then make it possible to prioritize planting in green belts (peri-urban), in streets, and in institutional spaces.

Carbon stock (amount of carbon at a particular time) is different from the carbon sequestration rate (rate of carbon taken up over time). In the present study, carbon stock is estimated from allometry, and an average annualized accumulation is calculated by dividing the carbon stock by the cohort age. Species are completely confounded with cohort age and site history since the two species are as two different age cohorts planted in the same year on the same street. The study is thus not designed to show a species effect as it is a comparison between two purposively selected cohorts. The purpose was to: (i) take diameter at breast height and height measurements of sampled trees of both species; (ii) obtain dates of planting the cohorts; (iii) estimate aboveground carbon stock by applying appropriate allometric equations; (iv) calculate average annualized accumulation (aboveground carbon

stock divided by the age); and (v) test the null hypothesis that the mean annualized accumulation is not different between the two cohorts.

Materials and methods

Study area

Fieldwork was carried out in Dutse town of Dutse Local Government Area (LGA), Jigawa State, Nigeria (latitude 11.70° N and longitude 9.34° E) during the month of October/November 2021, as depicted in Figure 1. Dutse is the administrative capital of Jigawa State and has a tropical Sudan-savanna climate with rainfall concentrated in a few months (June to September), a long dry season, and high annual mean temperature all year round. Soils in built-up areas are mostly sandy to sandy loam, and are often compacted and disturbed at the time of construction, with mean monthly temperatures of approximately 21 °C to 38 °C. Vegetation is typical Sudan savanna with scattered trees and shrubs (Amoo *et al.,* 2024).

The study street, Muhammad Saad Abubakar Street, is approximately 1.2 km long and accommodates a variety of mature ornamental and shade trees, including stands of *F. benjamina* and *T. mantaly*. The trees are planted in an avenue pattern, one row on either side of the street at a spacing of about 8-10 m. Management includes occasional pruning by the municipality, supplemental watering for young trees and no fertilization. The two species are growing as even-aged cohorts that can be compared, where by figure 1 provides a map of the study area.

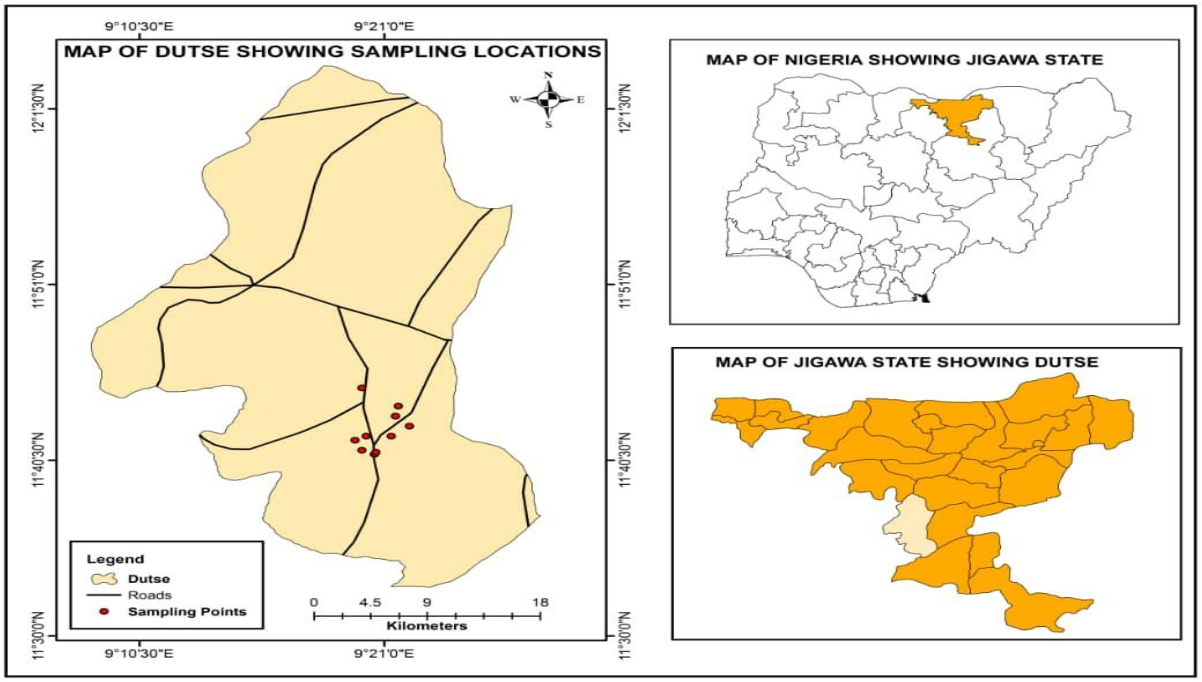


Figure 1. Map of the study area showing Muhammad Saad Abubakar Street, Dutse, Jigawa State, Nigeria, and the locations of sampled Ficus benjamina and *Terminalia mantaly* trees.

Sampling design

Ten individuals of *F. benjamina* and 10 individuals of *T. mantaly* were selected using purposive sampling design. The criteria used for inclusion were: single main stem, no

damage to the crown, bole accessible for measurement, and belonging to a cohort of known planting dates. Planted dates for plants were confirmed using municipal planting records, estate maintenance records and from oral interviews with long-term residents and municipal arborists (where possible). The trees in the *F. benjamina* cohort were planted around 2014 (7 years old at survey) and those in the *T. mantaly* cohort were planted around 2003 (18 years old at survey).

The decision to undertake a purposive sample was due to the fact that the street-tree population throughout the city was the product of street tree planting campaigns of the past rather than a continuous mixed-aged forest. The design is based on comparison between similar groups of trees (e.g. even-aged cohorts) only, and not between all trees within the city. Each tree (n = 10 per species) is the inferential unit. It is explicitly recognised that species is entirely confounded with cohort age and site history and that the design is unable to discern a species effect.

Field measurements

Stem circumference was determined at 1.3 m above the ground (breast height) with a standard measuring tape. Circumference (cm) was divided by π to determine Diameter at Breast Height (DBH, cm). The height of the trees was recorded with a clinometer. The horizontal distance between the observer and the stem was measured and the angle of elevation to the top of the crown and the angle of declination to the base of the stem was noted. The height was determined as follows:

$$h = (d \cdot \tan \theta_{elevation} + d \cdot \tan \theta_declination) \quad (1)$$

where d is the horizontal baseline distance, and θ are the measured angles. All measurements were made under low-wind conditions (< 5 km/h) to reduce clinometer error.

All instruments were checked before each day of field work, and all measurements were recorded on a pre-made data sheet and then double entered for accuracy; DBH was taken at the marked point on the stem so as to be consistent; and the same observer took all measurements and made sure the trees were measured twice.

Biomass and carbon estimation

Aboveground green weight (GW, kg) was calculated with diameter-class allometric equations most commonly used for non-destructive urban tree assessment (Nowak *et al.,* 2013; Conti *et al.,* 2019):

$$For\ DBH\ < 28cm: GW = 0.577\ \times D^2\ \times H) \quad (2)$$

$$For\ DBH\ \geq 28cm: GW = 0.0346\ \times D^2\ \times H) \quad (3)$$

The formula is: where D is DBH (cm) and H is total tree height (m) and GW is (kg). These equations were developed and tested for general use to model broadleaf urban trees in the DBH range of about 5–100 cm in temperate and subtropical urban forests, where calibration is achieved by destructive harvesting. They describe small and large stems of different form factors. They have not been calibrated locally for *F. benjamina* or *T. mantaly*, and this is recognized as an area of uncertainty.

The two conversion factors used were:

a. Average moisture content of woody biomass at the time of estimation (GWD – Green to dry conversion): dry weight = 0.5 × GW.
b. Dry-to-carbon conversion: carbon stock = 0.5 × dry weight with the default carbon fraction of the broadleaf species from IPCC (2006) and Chave *et al.* (2014).

Average annualized carbon accumulation (kg C year^{-1}) was calculated for each tree as:

$$Annualizes\ accumulation = carbon\frac{stock}{cohort}age\ (years) \quad (4)$$

This linear normalization gives an equivalent measure for known-age cohorts but does not provide a measure of current sequestration rate, and cannot be used in place of growth-curve models where repeated measurement data or dendrochronology is available.

Statistical analysis

Means, sample standard deviations, and ranges were calculated for each species in terms of height, carbon stock, and annualized accumulation. The mean annualised accumulation for cohorts was compared using an independent-samples Student's t-test (two-tailed). The level of significance was set at α = 0.05. With $n_1 = n_2 = 10$, df = 18 and the critical t value was approximately 2.101. Assumption tests consisted of normality (SHAPIRO-WILK) and homogeneity of variance (LEVENE). The effect size was reported as Cohen's d and the 95% confidence interval of the mean difference was calculated. Robustness was tested by performing a sensitivity analysis with alternative values for the C fractions (0.45 and 0.50) and ±10% variation in allometric Ks. All the analyses were performed using the standard statistical software.

Results

Tree size and age structure

There were no differences in mean age of sampled *F. benjamina* trees or *T. mantaly* trees, and all were 7 years and 18 years old, respectively. Table 1 shows the raw values of DBH and height of each tree. Heights of *F. benjamina* ranged from 5.00 to 14.62 m (mean 9.44 ± 3.12 m). Heights of *T. mantaly* ranged from 19.51 to 33.52 m (mean 25.84 ± 4.12 m). The increase in the mean height of *T. mantaly* is in line with its age and its growth form as a medium-to-large street tree (Figure 2).

Table 1. Raw DBH and height values for sampled trees (n = 10 per species).

Tree no.	*F. benjamina* DBH (cm)	*F. benjamina* height (m)	*T. mantaly* DBH (cm)	*T. mantaly* height (m)
1	21.4	8.20	34.7	24.10
2	15.9	6.10	41.2	28.50
3	16.2	6.40	36.8	26.30
4	14.8	5.00	38.4	27.10
5	27.6	14.62	44.1	33.52
6	18.5	8.10	37.2	25.80
7	17.1	7.90	32.5	22.40
8	19.3	9.30	33.9	23.70
9	18.8	9.10	29.6	19.51
10	24.2	12.10	35.8	24.30

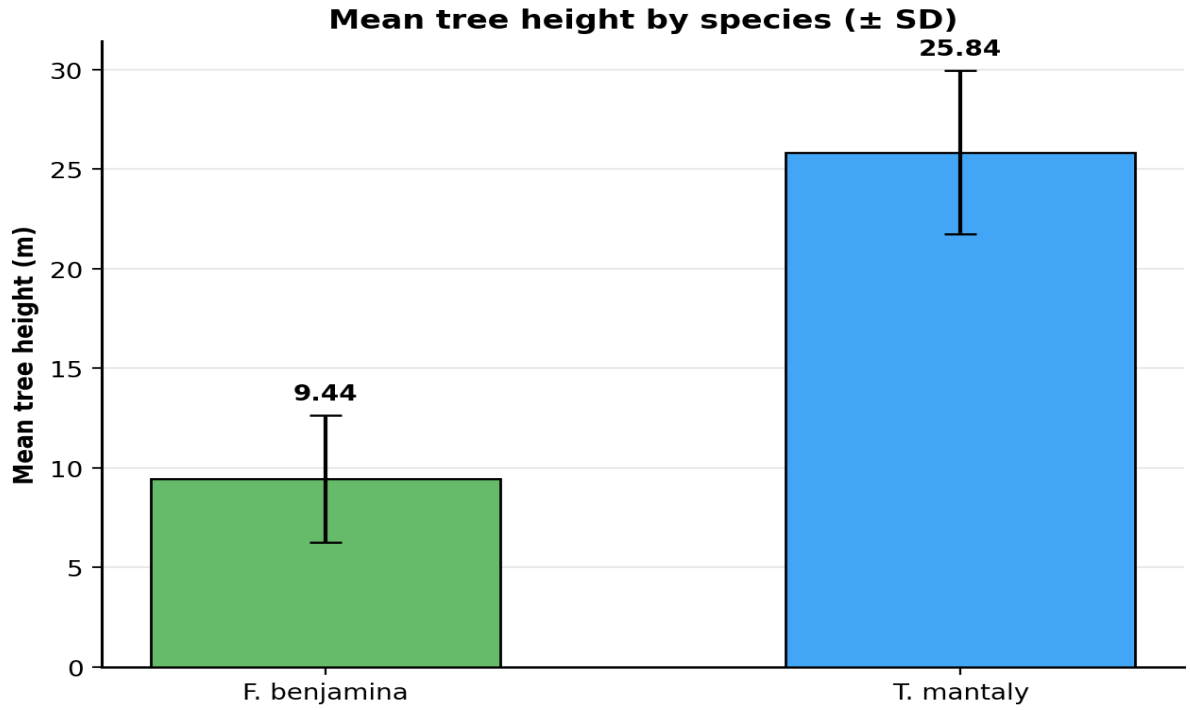


Figure 2. Mean tree height (± SD) of *Ficus benjamina* and *Terminalia mantaly* street trees in Dutse, Nigeria

Aboveground carbon stock

Mean aboveground carbon stock was 72.2 ± 34.1 kg C tree^{-1} for *F. benjamina* and 458.3 ± 138.2 kg C tree^{-1} for *T. mantaly* (Figure 3). Individual stocks ranged from 38.94 to 136.92 kg C tree^{-1} for *F. benjamina* and from 207.07 to 661.65 kg C tree^{-1} for *T. mantaly*. Table 2 provides a reproducible calculation table for calculating DBH, height, GW, dry weight, carbon stock, and annualized accumulation for each tree.

Table 2. Reproducible calculation of aboveground green weight, dry weight, carbon stock, and annualized accumulation for each sampled tree.

Tree no.	Species	DBH (cm)	H (m)	Equation used	GW (kg)	Dry weight (kg)	Carbon stock (kg C)	Age (yr)	Annualized accumulation (kg C yr^{-1})
1	*F. benjamina*	21.4	8.20	GW=0.0577·D²·H	82.6	41.3	20.65	7	2.95
2	*F. benjamina*	15.9	6.10	GW=0.0577·D²·H	87.9	44.0	22.00	7	3.14
1	*T. mantaly*	34.7	24.10	GW=0.0346·D²·H	1013.0	506.5	253.25	18	14.07
2	*T. mantaly*	41.2	28.50	GW=0.0346·D²·H	1859.0	929.5	464.75	18	25.82

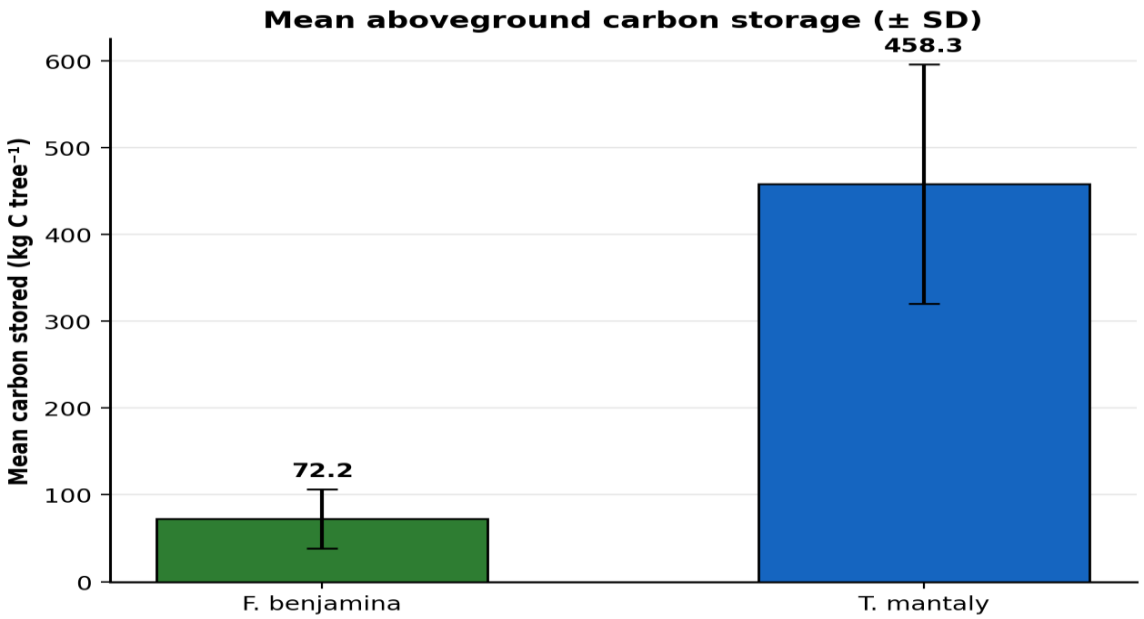


Figure 3. Mean aboveground carbon stock (± SD) per tree by species.

Average annualized carbon accumulation

Mean annualized accumulation was 10.12 ± 4.92 kg C year^{-1} for *F. benjamina* and 25.46 ± 7.65 kg C year^{-1} for *T. mantaly* (Figures 4 and 5). The range of individual values varied between 5.56 kg C year^{-1} and 19.56 kg C year-1 for F. benjamina and 11.50 kg C year-1 and 36.76 kg C year^{-1} for *T. mantaly*. The older and larger *T. mantaly* cohort had more than twice the mean annualized accumulation of the younger *F. benjamina* cohort. This difference is not attributable to species identity alone due to the confounding of age and species.

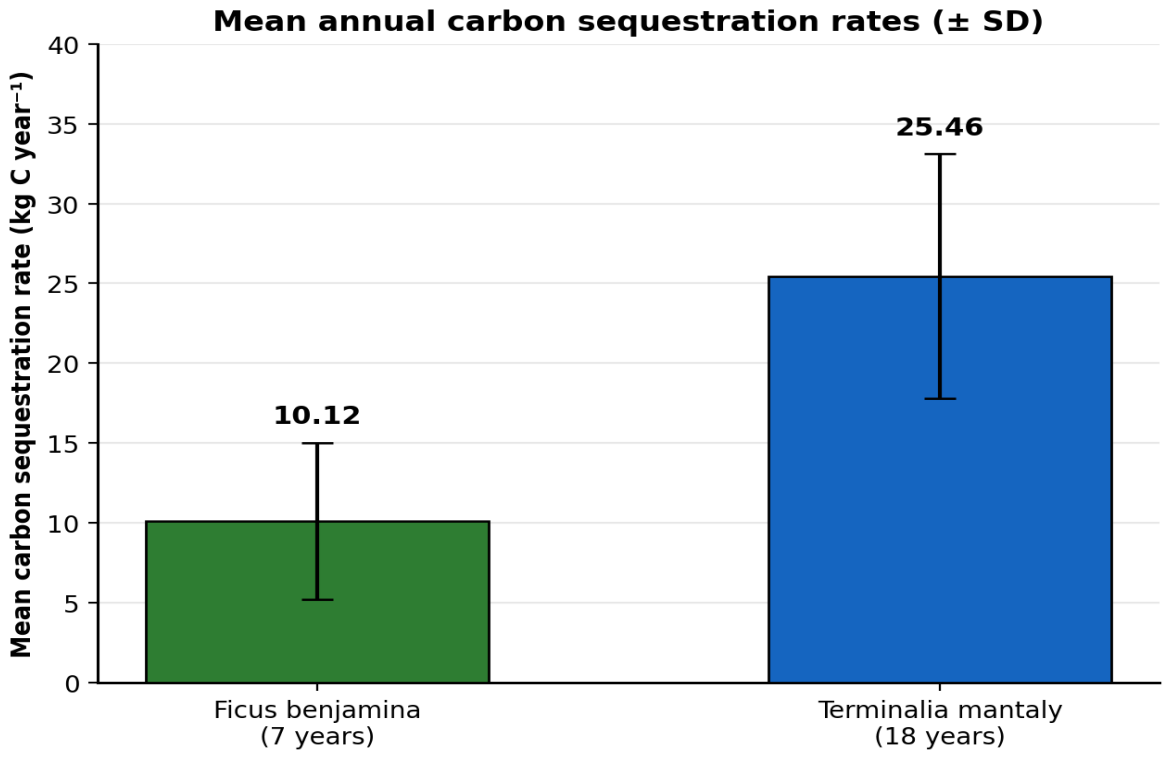


Figure 4. Mean annualized carbon accumulation (± SD) by species.

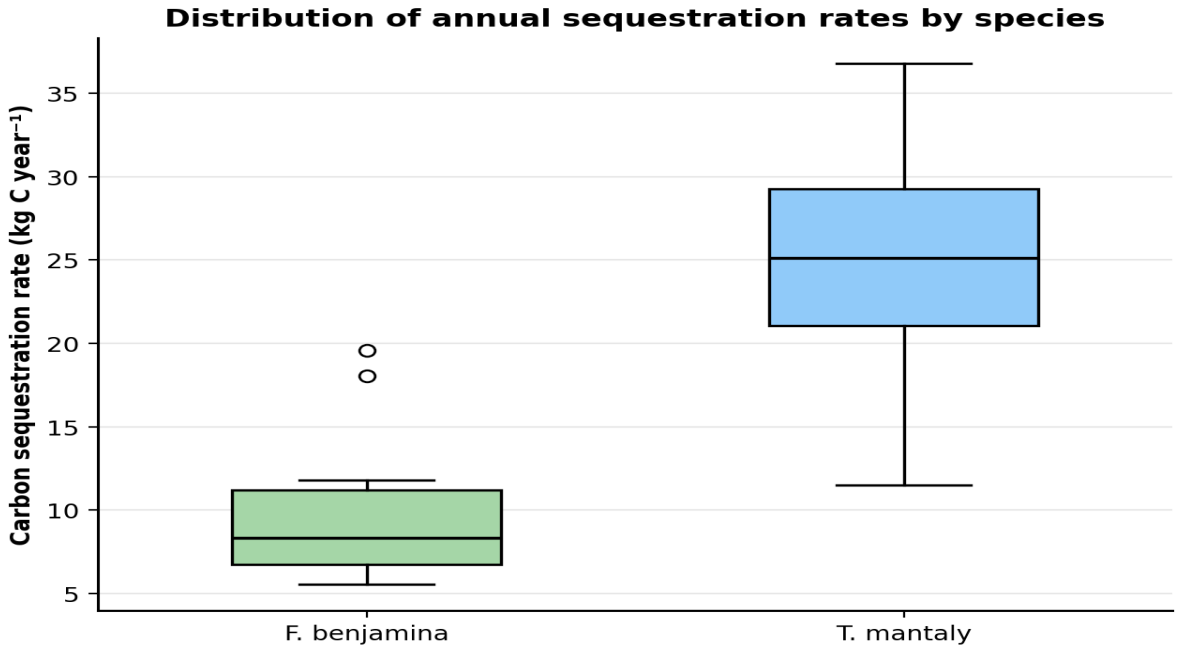


Figure 5. Distribution of individual-tree annualized carbon accumulation (boxplot) for each species.

Table 3. Individual annualized carbon accumulation (kg C year^{-1}).

Tree no.	*F. benjamina*	*T. mantaly*
1	11.80	20.83
2	6.28	35.80
3	6.52	27.27
4	5.56	27.93
5	19.56	36.76
6	7.39	29.68
7	8.69	20.11
8	7.94	21.75
9	9.39	11.50
10	18.06	22.96
Mean ± SD	**10.12 ± 4.92**	**25.46 ± 7.65**

Hypothesis test

Mean annualized accumulation was compared in the independent-samples t-test. Results were: t = 5.33, df = 18, p = 0.00004. The mean difference was 15.34 kg C year^{-1} (95% CI: 9.29–21.39), and Cohen's d was 2.38 (large effect). Assumption checks: Shapiro-Wilk tests showed that both species were normally distributed ($p > 0.05$), and Levene's test showed homogeneity of variance (p = 0.28), both of which were acceptable. The sensitivity analysis involved using carbon fraction of 0.45 and 0.50 and varying allometric coefficients within ±10% of the values did not alter the significant difference conclusion. Thus, the null hypothesis of no difference in mean annualized accumulation between the two cohorts was rejected at the 5% significance level.

Table 4. Inferential statistics for the comparison of mean annualized carbon accumulation.

Statistic	Value
T	5.33
Df	18
p-value (two-tailed)	0.00004
Mean difference (kg C yr^{-1})	15.34
95% CI for mean difference	9.29 – 21.39
Cohen's d	2.38
Shapiro-Wilk (*F. benjamina*)	p > 0.05
Shapiro-Wilk (*T. mantaly*)	p > 0.05
Levene's test	p = 0.28

Discussion

Interpretation of cohort differences

The higher mean carbon stock and annualized accumulation in the *T. mantaly* cohort are consistent with its greater age and larger stature. Larger stem size and crown size are proportionately more important for the contribution to aboveground carbon (Stephenson *et al.,* 2014; Köhl *et al.,* 2017), and older trees have more time to accumulate biomass. The two species are, however, completely confounded by site history and cohort age since both are encountered as two distinct even aged cohorts along the same street. This is because the difference in annual accumulation cannot be attributed to a species effect. Although the age-normalized metric is still valuable as a descriptive comparison of the two cohorts, it does not separate out intrinsic differences in growth or carbon accumulation between the two species.

There was significant variation within each cohort. Variations in annualized accumulation exceeded threefold even within *F. benjamina*, and were likewise significant within *T. mantaly*. This is typical of variation among street trees planted in soils with different volumes, compaction, irrigation, pruning, and microclimates (Nowak *et al.,* 2013). The quality of the microsite and management history should then be considered as important covariates to be included in any operational carbon inventory.

Methodological uncertainty

The allometric equations presented here are from broadleaf urban trees in temperate and subtropical regions and have not been locally validated for *F. benjamina* or *T. mantaly*. The density, form factors, and biomass partitioning of a wood may not be the same as the species used in calibration. The two consecutive conversion factors of green to dry and dry to carbon are standard approximations that add to the uncertainty. Measurements of below ground biomass and soil carbon were not made and total ecosystem carbon is therefore under-estimated. The linear normalization of stock by age assumes that the stock has been increasing linearly over time and does not account for known non-linear patterns (Stephenson *et al.,* 2014). Sensitivity analysis showed that the results do not change significantly for sensitivity in these assumptions, but the actual values should be regarded as estimates, not precise measurements.

Comparison with other studies

Comparisons with other studies are limited by differences in allometric models, climate, age structure and belowground biomass. However, the mean values of annualized accumulations reported here were within the range of young to mid-aged, urban trees in seasonal tropical climates. For instance, the mean sequestration rates of urban Eucalyptus and Cupressus species were tens of kilograms of carbon per year per tree at Duhok Province, with Eucalyptus sequestered more than Cupressus (Saeed *et al.,* 2016). Several species were observed in the tropics with higher rates in older or more productive stands (Eneji *et al.,* 2018; Jithila & Prasadan, 2018). The rates recorded for *F. benjamina* in the present young cohort at Dutse are similar to or higher than those recorded in a university in Noida, and the higher emission areas in Makurdi, which may be due to differences in age, site fertility and methodology. These comparisons confirm the requirement for site specific calibration.

Implications for urban forestry in Northern Nigeria

T. mantaly emerged as an additional use tree with a higher estimated carbon stock and annualized accumulation per tree in the sampled cohort and has the potential to be used in municipal and state planting programmes for trees in Sudan-savanna towns such as Jigawa. *F. benjamina* continues to be useful for amenity, structural diversity and when a smaller, more manageable crown is required. Ideal portfolios must be an optimal balance between carbon, cooling, biodiversity, infrastructure compatibility, and maintenance cost (Escobedo *et al.,* 2019; Pataki *et al.,* 2021). Public planting can be improved by carbon metrics for enhancing the climate co-benefit profile of public planting. The implications in this design, however, are tentative because age as well as species is confounded with site, and cannot be used to give firm species-selection guidelines without age-matched, replicated, longitudinal data. Because this hectare scale extrapolation was not reported and did not fit with the study design, it has been removed.

Limitations and future research

There are some limitations to the findings. The small number of subjects per species (n = 10 per species) and the one street-corridor limits the generalizability of geographic generalization. No species effect could be found because species is completely confounded with cohort age and site history. There were no locally calibrated allometric equations, and there may be different wood densities and form factors in the calibration. These are the typical 50% dry-matter and 50% carbon assumptions. It was not possible to include belowground biomass and soil carbon, which would lead to underestimation of ecosystem carbon. Non-linear growth patterns cannot be captured by linear age normalization. The key strengths include the use of non-destructive techniques, verified planting records and open reporting of raw data and calculations. Ideally a stronger future design would be based on age-matched trees on a number of independent streets or sites, and repeated DBH measurements to estimate growth directly, with local allometric calibration, root and soil carbon sampling and long-term monitoring.

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Conclusion and reccommendations

This study estimates aboveground carbon stock and average annual carbon accumulation for two dominant street tree species in Dutse town, located at the northern part of Nigeria. The calculated aboveground carbon stock and aboveground carbon accumulation for the sampled older T. mantaly (18 years) were higher compared to the sampled younger *F. benjamina* (7 years), at 25.46 kg C year^{-1} and 10.12 kg C year^{-1}, respectively. Due to the complete confoundedness of species and cohort age, and site history, the study did not make the conclusion that *T. mantaly* sequesters carbon more quickly than *F. benjamina*. The species can both help reach local environmental quality and climate mitigation targets. Based on these results, the following suggestions are offered:

a. Shade and carbon-benefit planting programmes in Dutse and other towns and cities could potentially expand the use of *T. mantaly*, provided there is a mix of other species like *F. benjamina* and indigenous species, but after replicated and age-matched trials have shown differences.
b. State and local governments should establish regional inventories and have all species measure DBH, height and tree age in the same way to develop a local evidence base.
c. Long-term growth monitoring and local calibration of allometric equations and integration of root and soil carbon pools should be encouraged in research institutions.
d. Planning and assessing afforestation and desertification-control projects should include carbon and other ecosystem-service indicators and explicitly recognize and track co-benefits of climate.

Declarations

Author contributions (CRediT): *Not applicable*

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Ethics approval and consent (where applicable): *Not applicable*

Data availability: *Not applicable*

Use of AI tools (where applicable): *Not applicable*

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