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Research article (Araştırma makalesi)

Tree growth characteristics, stand productivity and carbon storage in age series indigenous species demonstration plantations in Forest Research Institute of Nigeria

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Abstract: Forest plantations are important in meeting national and global demand for industrial wood due to their fast growth rate and high productivity. They can produce 3–10 times higher biomass than natural forests, making them important for climate change mitigation. We examined the growth characteristics, productivity and carbon storage of age series *Nauclea diderrichii and Terminalia ivorensis* plantations at Forestry Research Institute of Nigeria. Tree growth variables were measured in 25 m x 25 m temporary sample plots selected from 6 to 24 years plantations of the two species. Biomass data were obtained through non-destructive means. Mean diameter at breast height (DBH) ranged from 13.3 cm (6 years) - 37 cm (24 years) in *T. ivorensis* and 18.3 cm (13 years) - 22.4 cm (14 years) in *N. diderrichii* stands while mean total height varied from 10.1 m - 21.2 m and 16.5 m - 17.8 m in respective plantations of the two species. Both species demonstrated a high degree of merchantability, with no difference between them (66.5 - 81.4% in *T. ivorensis* and 77.0 - 77.2% in *N. diderrichiii*). Mean basal area, volume, biomass and carbon stock in *T. ivorensis* stands were: 9.4 - 19.4 m^2/ha, 63.5 - 252 m^3/ha, 48.8 t/ha - to 188.6 t/ha and 24.4 t/ha - 94.3 t/ha, respectively while they were 12.0 m^2/ha - 12.1 m^2/ha, 118.4 m^3/ha - 195.8 m^3/ha, 187.0 t/ha - 214.6 t/ha and 93.5 t/ha - 107.3 t/ha in *N. diderrichii* plantations. The two tree species have a good growth rate and productivity when compared with some tropical plantation tree species. The productivity, merchantability, biomass and carbon stock of *N. diderrichii* and *T. ivorensis* stands are indicating their suitability as candidates for good quality timber, carbon sequestration and climate change mitigation.
Keywords: Carbon storage, Climate change, Forest plantation, Growth characteristics, Merchantability

Nijerya Orman Araştırma Enstitüsü'nde yerli tür deneme plantasyonlarında yaşa bağlı meşcere verimliliği, karbon depolama ve ağaç büyüme özellikleri

Öz: Plantasyonlar, hızlı büyüme potansiyelleri ve yüksek verimlilikleri sayesinde endüstriyel oduna yönelik ulusal ve küresel talebin karşılanmasında önemli bir yere sahiptir. Doğal ormanlardan 3 ila 10 kat daha fazla biyokütle üretebilmeleri nedeniyle iklim değişikliğiyle mücadelede de önemli yere sahiptirler. Bu çalışmada, Nijerya Orman Araştırma Enstitüsü'ndeki farklı yaşlardaki *Nauclea diderrichii* ve *Terminalia ivorensis* plantasyonlarının büyüme özellikleri, verimlilikleri ve karbon depolama kapasiteleri incelenmiştir. Büyüme parametreleri, her iki türe ait 6 ile 24 yaş aralığındaki plantasyonlardan seçilen 25 m x 25 m boyutundaki örnek alanlarda ölçülmüştür. Biyokütle verileri tahribatsız ölçüm yöntemleriyle elde edilmiştir. Ortalama göğüs çapı (DBH), *T. ivorensis* meşcerelerinde 13,3 cm (6 yaş) ile 37 cm (24 yaş) arasında ve *N. diderrichii* meşcerelerinde 18,3 cm (13 yaş) ile 22,4 cm (14 yaş) arasında değişirken; ortalama boylar sırasıyla 10,1 m - 21,2 m ve 16,5 m - 17,8 m aralığındadır. Her iki tür de yüksek derecede ticari kullanılabilirlik göstermiş olup, türler arasında istatistiksel anlamda bir farklılık tespit edilmemiştir (*T. ivorensis*'te %66,5 - %81,4 ve *N. diderrichii*'de %77,0 - %77,2). *T. ivorensis* plantasyonlarında ortalama göğüs yüzeyi, hacim, biyokütle ve karbon stoku sırasıyla: 9,4 - 19,4 m²/ha, 63,5 - 252 m³/ha, 48,8 t/ha - 188,6 t/ha ve 24,4 t/ha - 94,3 t/ha olarak belirlenirken, *N. diderrichii* plantasyonlarında bu değerler 12,0 m²/ha - 12,1 m²/ha, 118,4 m³/ha - 195,8 m³/ha, 187,0 t/ha - 214,6 t/ha ve 93,5 t/ha - 107,3 t/ha'dır. Bu iki ağaç türü, diğer bazı tropikal plantasyon ağaç türleri ile karşılaştırıldığında iyi bir büyüme hızı ve verimlilik sergilemektedir. *N. diderrichii* ve *T. ivorensis* meşcerelerinin verimliliği, ticari kullanılabilirliği, biyokütlesi ve karbon stoku; bu türlerin kaliteli kereste üretimi, karbon tutumu ve iklim değişikliği ile mücadele açısından uygun türler olduğunu göstermektedir.
Anahtar kelimeler: Karbon depolama, İklim değişikliği, Plantasyon, Büyüme özellikleri, Piyasaya uygunluk

1. Introduction

The global area of forest plantations has been increasing since the middle of the 20th century (Evans and Turnbull, 2004; Payn et al., 2015; FAO, 2018; Onyekwelu, 2020). By the year 2022, the total global area of planted forest had risen to about 294 million hectares, up from about 17.8 million hectares in 1980 (FAO, 1992; Evans and Turnbull, 2004; FAO, 2022). Available information revealed that planted forests account for 7.35% of total global forest cover (FAO, 2022; Xu et al., 2024) and are estimated to contribute about

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4.60% (12.85 Pg C) of global forest biomass carbon (Xu et al., 2024).

Exotic tree species dominate the establishment and expansion of forest plantations, especially in the tropical regions of the world (Onyekwelu, 2020) such as Nigeria, which are attributed to the fast growth rates, short rotation lengths and pioneer-type species of exotic tree species. Records indicate that until the early 1960s, forest plantation establishment in Nigeria was dominated by indigenous species like *Nauclea diderrichii*, *Terminalia* species *Triplochiton scleroxylon*, *Mansonia* species, among others (Onyekwelu et al., 2003). For instance, over 82,400 hectares of plantations were established between 1970 and 1984, and by 1997 Nigeria's total plantation area had reached approximately, 150,000 hectares. This also rose to 196,000 hectares by 1998 and 382,000 hectares by the year 2010 (Onyekwelu et al., 2003). However, the advent of large-scale plantations with exotic species like *Gmelina arborea, Tectona grandis*, *Eucalyptus* species and *Pinus* species, led to a situation where the indigenous tree species became neglected. Consequently, little emphasis was placed on the establishment of more plantations of indigenous tree species and the understanding of their growth characteristics. Recently, there has been renewed interest in establishing plantations with indigenous tree species. The Forestry Research Institute of Nigeria (FRIN) is among the organisations in Nigeria establishing demonstration plantations of indigenous tree species.

Franklin and Mercker (2009), opined that if renewable forest resource is to be used as a tool to combat climate change, then understanding species' growth characteristics becomes essential for effective management. As a tree grows, it captures and stores carbon in both above and below ground components. However, it dies and decomposes, much of this stored carbon is released back into the atmosphere (Franklin and Mercker, 2009). Therefore, maintaining healthy stands in forest reserves, plantations, urban parks, community woodlots and arboretums among others, would contribute to reverse the effects of climate crisis. It is expected that forests would not only produce a high amount of biomass but also fulfil various ecosystem functions (Zeller and Pretzsch, 2019). An understanding of tree growth characteristics is beneficial for the management of planted and natural forest ecosystems and can aid in maintaining appropriate stocking, pruning, thinning and other treatments as well as achieving healthy and productive forest.

Forests function as carbon sink, storing about 45% of terrestrial carbon, but if not properly managed, forests can be a leading source of carbon emissions from deforestation and forest degradation (Bonan, 2008; Keith et al., 2009) and other anthropogenic activities. For instances, between year 2010-2019, land-use change, including deforestation accounted for about 5.1 ± 2.6 GtCO_2 per year (IPCC, 2021) while FAO (2020), report revealed that deforestation alone released about 3.0 GtCO_2 per year globally between 2015-2020. However, the forest if managed adequately can contribute significantly to solving the climate crisis confronting humanity (Godfrey and Tunhuma, 2020). Several initiatives are proffered to fight climate crisis, among which is tree planting. Forest plantations have been noted to account for about 7% of the 662 Pg C sequestered in global forest ecosystems (Pugh et al., 2019; FAO, 2020; 2022) thus making them one of the greatest contributor to forest carbon (C) sink (Pugh et al., 2019). In this study we examine the growth characteristics, stand productivity and carbon storage of two indigenous tree species (*Nauclea diderrichii* and *Terminalia ivorensis*) demonstration plantations established within the forested section of FRIN. It is hoped that the information from this study will improve our understanding of the growth habits of the investigated tree species and thus beneficial towards the management in the event of large-scale establishment of their plantations.

2. Materials and methods

2.1. The study area

This study was carried out at the forest plantation demonstration plots of Forestry Research Institute of Nigeria (FRIN). The plantations were established within the forested area of the headquarters of FRIN, located at Jericho Hill reserve, Ibadan, Nigeria (Figure 1). The FRIN headquarters is found between latitude 07° 25′ N and 07° 55′ N and longitude 3° 9′ E and 3° 53′ E, within the tropical wet and dry climate of Nigeria, which consists of a long rainy season (March to November) and a relatively short dry season (December to March). Rainfall pattern is bimodal with two peaks (July and September) and is characterized by heavy and consistent rainfall, with an average annual rainfall of 1420 mm. The study area has a warm climate, with mean daily temperature ranging from 18.7°C to 34.4°C, depending on the season. The dry season is relatively dry, though there can be little rainfall during this season, resulting in a situation where the soil of the study area is rarely totally dry, which explains why tree growth is continuous throughout the year. Mean relative humidity is approximately 82% and 60% during rainy and dry seasons, respectively (Awosusi et al., 2020). Soil texture ranges from loamy sand in surface horizons to sandy loam and sandy clay loam in subsurface horizons, which explains why the soil exhibit slight stickiness at subsurface horizons (Onemayin et al., 2020; Isola et al., 2021). The soil is medium-textured, with high inherent fertility and high base status (Isola et al., 2021).

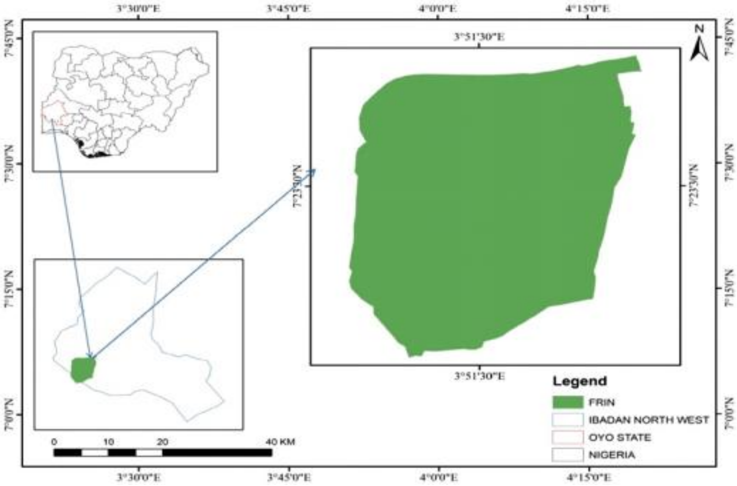

Figure 1. Map of Forestry Research Institute of Nigeria

2.2. Brief history of Forestry Research Institute of Nigeria

Forestry Research Institute of Nigeria (FRIN) was established as a Federal Department of Forestry Research in 1954 but in 1977 its status was changed to Research Institute, a status it maintains to date. The mandate of FRIN is to conduct research into all aspects of forestry, forest products utilization, watershed management, wildlife, agroforestry, among others and to train technical manpower for forestry and related fields. The focus of FRIN is to apply scientific knowledge to management and conservation of forest resources in Nigeria in a way that meets the needs of present and future generations (Onyekwelu, 2024). In addition to research at its headquarters at Ibadan, FRIN research activities are also carried out at 17 hubs and research stations spread across all ecological zones of Nigeria; 7 specialised Departments and 4 research centres. FRIN's headquarters sits on 104.89 ha, out of which 19.73 ha are a built-up area while the remaining 85.16 ha remain under forest cover (natural and plantation forests). One of the means through which FRIN strives to meet its mandate, is the establishment of demonstration forest plantations within its headquarters and outstations. Forest plantation establishment at FRIN headquarters commenced about 25 years ago. Since then, both indigenous and exotic tree species have been established with *N. diderrichii, Terminalia. superba, T. ivorensis, Gmelina arborea* and *Khaya senegalensis* being the prominent tree species.

2.3. Description of T. ivorensis and N. diderrichii tree species

T. ivorensis is a large deciduous tree commonly known as black Afara in the family of Combretaceae. Native to West and Central Africa (Keay, 1989). It thrives best in moist semi-deciduous and evergreen forests. It can attain heights of 30 – 45 cm with a straight, cylindrical bole often free of branches up to 20 cm and reaching diameters of 1 – 1.5 m (Keay, 1989). It has spreading crown and characteristic whorled branching. It is moderately heavy, durable and resistant to termite. It is light demanding and thrives well in plantations. It is widely used for furniture, construction, plywood and joinery (Keay, 1989). Also, economically valuable for timber, reforestation, and as a plantation species. Based on IUCN status, it is classified as vulnerable due to overexploitation and habitat loss (IUCN, 2021).

N. diderrichii is a large evergreen hardwood species in the family Rubiaceae. It grows up to 40 – 50 m in height and up to 2 m in diameter (Keay, 1989). The wood is extremely durable and resistance to fungi and termites. It is used for bridges, railway slippers, decking and so on. However, owing to decline in its population due to logging and forest conversion, it is has been classified as vulnerable in IUCN status (IUCN, 2021).

2.4 Method of data collection and data processing

Data for this study were collected from unthinned even-aged plantations of *T. ivorensis* and *N. diderrichii,* established within the forested area FRIN headquarters. Data were collected from plantations of two tree species ranging from 6 to 24 years old. The stands of each tree species' plantations were divided into temporary sample plots of 25 m x 25 m, from which three to five plots were randomly selected. Complete enumeration of all trees within each sample plots was carried out. The following measurements were made on all trees: diameter at breast height (DBH), diameters at the base, middle and top of the tree, total height, merchantable height, crown height and crown diameter.

2.5. Data processing

Basal Area computation: The basal area of each tree was estimated using equation 1 (Hutsch et al., 2003). Total basal area was computed for each sample plot and then extrapolated to per hectare by multiplying the mean plot basal area by 16 (i.e. the number of 25 x 25 m plots per hectare).

$$BA = \frac{\pi DBH^2}{4} \quad (1)$$

Where, BA = Basal Area (m^2), π = 3.142 (constant), DBH = diameter at breast height (m).

Volume computation: The volume over bark of each tree was estimated using Newton-Riecke formula (Husch *et al.*, 2003; equation 2). Afterwards, total stand volume was computed by first estimating total volume for each sample plot and then extrapolating it to volume per hectare by multiplying the plot mean volume by 16 (i.e. number of 25 x 25 m plots per hectare).

$$\text{Vol} = \pi H \left[\frac{D_b{}^2+4D_m{}^2+D_t{}^2}{24}\right] \quad (2)$$

Where Vol = Volume over bark (m^3), H = total height (m), D_b = Diameter at the base, D_m = Diameter at the middle, D_t = Diameter at the top and π = 3.142 (constant).

Tree slenderness coefficient (SLC): Tree slenderness coefficient often serves as an index of tree stability (Onilude and Adesoye, 2007). The slenderness coefficient of each tree was estimated by dividing the total height of a tree by its DBH as shown in equation 3.

$$\text{SLC} = \frac{\text{Tht}}{\text{DBH}} \quad (3)$$

Where: Tht = tree height (m) and DBH = Diameter at breast height (m)

Afterwards, the SLCs of all individual trees were classified into three coefficient classes following the recommendation of Onilude and Adesoye, (2007) as shown below.
Slenderness coefficient Class 1: SLC values > 99
High slenderness coefficient
Slenderness coefficient Class 2: 70 < SLC values < 99
Moderate slenderness coefficient
Slenderness coefficient Class 3: SLC values < 70
Low slenderness coefficient.

2.6 Estimation of aboveground biomass

The aboveground biomass of standing trees in each plot was estimated through non-destructive means using equation 4, which was recommended by Brown and Lugo (1992).

$$AGB = BEF \; x \; VOB \; x \; WD \quad (4)$$

Where: AGB = Aboveground Biomass, BEF = Biomass Expansion Factor; VOB = Volume over bark (m^3); and WD = Wood density (g/cm^3).

Wood density for each tree species was obtained from Global Wood Density Database (Zanne et al., 2009). Biomass expansion factor (BEF) of 1.74 was used to account for the biomass of non-merchantable components of each tree as suggested by Brown and Lugo (1992), for the tropical rainforest ecosystem. Aboveground biomass per plot was obtained by summing the biomass of all trees in the plot while biomass per hectare was estimated by extrapolating the mean plot biomass to biomass per hectare following the procedure adopted for basal area and volume per hectare as outlined above.

2.7 Carbon Sequestered by the Trees

The carbon content of any forest tree is estimated to be about 50% of its biomass as adopted by research workers (Sharma et al., 2020; Akintunde-Alo et al., 2024; Onyekwelu et al., 2024). Therefore, the amount of carbon sequestered by each tree was calculated by multiplying the AGB value by 0.5 as shown in equation 5.

$$Cs = AGB \; x \; 0.5 \quad (5)$$

Where: Cs = sequestered carbon in t/ha, AGB = above ground biomass in t/ha

2.8 Data analysis

Statistical analysis were performed to check if there are significant differences (H_0: $u_1 \neq u_2$) in growth variables (DBH, tree height, aboveground biomass) within and between *T. ivorensis* stands and *N. diderichii* stands. For *T. ivorensis* stands, one-way analysis of variance (ANOVA) was used to test the growth variables across the three age classes while independent sample t-test was employed for *N. diderichii* across the two age classes. Significant difference at $\alpha_{0.05}$ with treatment means separated by Tukey's Honestly Significant Difference (HSD) post mortem. All statistical analyses were performed using SPSS Statistics.

3. Results

As expected, the size of *T. ivorensis* trees increased with the plantation's age, which is evident from the increasing DBH (mean and maximum) with age. Mean DBH was 13.3 cm, 22.3 cm and 37 cm for 6, 13 and 24 year old plantations, respectively while maximum DBH was 24.0 cm, 37.8 cm and 61.1 cm, for the respective ages (Table 1). Mean total height varied from 10.1 m in 6 years old stand to 21. 2 m in 24 years old stand. The proportion of total height accounted for by crown height was not dependent on age. Crown height accounted for an average of 34.5% (range: 6 - 59.8%), 18.6% (range: 3.5 - 43.1%) and 24.8% (14 - 36.6%) of total height in 24, 13 and 6 years plantations, respectively. This result implies that merchantability of the *T. ivorensis* tree is not dependent on age judging from the trend of proportion of merchantable height to total height (81.4%, 75.2% and 66.5% in 13, 6 and 24 years, plantations, respectively). Crown diameter of the species increased with age. Mean crown diameter increased slightly from 5.3 m (range: 3.3 - 7.9 m) at 6 years to 6.6 m (range: 2.8 - 10.9 m) at 13 years but increased greatly to 10.3 m (range: 6.5 - 15.1 m) at age 24 years (Table 1).

Tree diameter distribution in *T. ivorensis* plantations followed a normal distribution pattern (Figure 2a). A high percentage (56.3%) of the trees fell within 10.1 – 20 cm DBH class, followed by trees in 20.1 - 30.0 cm DBH class, only few trees were found within small (< 10 cm) DBH (11.3%) and large (4.4%) DBH (> 40cm) class (Figure 2a). The total height of trees was evenly distributed. About 35.7% of all trees enumerated fell within the height class of ≤ 10 m, 39.8% of the trees were found within height class of 10.1 m – 20 m while 24.5% of the trees were observed within the height class of 20.1 m and above (Figure 2b).

There are indications that the stability of *T. ivorensis* trees increases with plantation age, judging from the increasing trend of the percentage of trees with low slenderness coefficient (SLC). Trees with low SLC accounted for 33.3%, 64.6% and 78.1% of all trees in 6-, 13- and 24-years plantations, respectively (Figure 3). About 50%, 16.7%, and 21.9% of trees in 6-year-old, 13-year-old, and 24-year-old plantations of the species were categorized into moderate SLC, while 16.7% and 18.8% of trees in 6-year-old and 13-year-old plantations fell within the high SLC category (Figure 3).

Table 1. Growth and yield characteristics of *T. ivorensis* plantations in the study area

	Plantation year/age											
	2000 (24 years)				2011 (13 years)				2018 (6 years)			
Variables	Mean	Min	Max	SEE	Mean	Min	Max	SEE	Mean	Min	Max	SEE
DBH (cm)	37.0[a]	18.0	61.1	1.64	22.3[b]	10.5	37.8	0.92	13.3[c]	6.0	24.0	0.33
Mht (m)	14.1	7.5	21.1	0.52	9.0	7.0	22.4	0.86	7.60	3.5	12.5	0.70
Tht (m)	21.2[a]	12.2	34.8	0.79	11.1[b]	9.2	25.6	1.01	10.1[c]	5.3	15.5	0.76
CD (m)	10.3	6.5	15.1	0.7	6.6	2.8	10.9	0.28	5.3	3.3	7.9	0.32
Stand density/ ha	171	128	240	-	277	224	352	-	629	528	752	-
Mean BA (m^2/ha)	19.4	14.9	23.4	0.01	12.3	12.1	12.5	0.00	9.4	9.0	9.3	0.00
Mean Mvol (m^3/ha)	170.0	127.4	201.6	0.10	60.6	43.2	88.4	0.03	50.8	48.3	52.3	0.02
Mean Tvol (m^3/ha)	252.0	166.4	342.1	0.13	74.0	56.2	104.8	0.04	65.3	61.9	67.5	0.02
Mean AGB (t/ha)	188.6	124.5	255.9	0.10	55.3	42.1	78.4	0.03	48.8	46.3	50.5	0.003
Mean Cs (t/ha)	94.3	62.3	128.0	0.05	27.7	21.0	39.2	0.03	24.4	23.2	25.3	0.003

Min – Minimum; Max – Maximum; SEE – Standard Error of Estimate; DBH – Diameter at breast height; Mht – Merchantable height; Tht – Total height, CD – Crown diameter; BA – Basal area; Mvol – Merchantable volume; Tvol – Total volume; AGB – Above ground biomass; Cs – Carbon sequestered

Stand density in *T. ivorensis* plantations was generally low and decreased with age, suggesting a high mortality rate at some time during the lifespan of the plantation or that thinning may have been applied. Mean stand density per hectare varied from 629 trees per hectare in 6 -year-old plantation to 171 in 24 -year-old plantation (Table 1). The maximum tree density of 752 trees per hectare was obtained from 6 -year-old plantation. Mean stand basal area was 9.4 m^2/ha, 12.3 m^2/ha and 19.4 m^2/ha for 6 -year-old, 13 -year-old and 24 -year-old plantations, respectively while mean total volume production was 63.5 m^3/ha, 74.0 m^3/ha and 252 m^3/ha for the respective plantations (Table 1). About 77.8%, 81.9% and 67.5% of the mean volume production in 6- year-old, 13-year-old and 24-year-old plantations were merchantable. Mean Aboveground biomass (AGB) production varied from 48.8 t/ha (range: 46.3 - 50.5 t/ha) in 6 years *T. ivorensis* plantation to 188.6 t/ha (range: 124.5 - 255.9 t/ha) in 24 years plantation (Table 1). Mean carbon storage varied from 24.4 t/ha (range: 23.2 - 25.3 t/ha) to 94.3 t/ha (range 62.3 t/ha - 128.0 t/ha).

Similar to *T. ivorensis*, the size of *N. diderrichii* trees increased with age, as revealed by the increasing growth variables with age, except mean basal area. Mean DBH was 22.4 cm and 18.3 cm for 14 -year-old and 13 -year-old plantations, respectively while maximum DBH was 33.3 cm and 33.6 cm, for the respective ages (Table 2). Mean total height varied from 16.5 m in 13 -year-old to 17.8 m in 14 -year-old stand. The proportion of total height accounted for by crown height was similar for both ages, with crown height accounting for an average of 22.8% (range: 1.2 - 44.2%) and 23.0% (8.1 - 52.6%) of total height in 13 -year-old and 14 -year-old plantations, respectively. The merchantability of *N. diderrichii* tree was similar in the two plantations (77.2% and 77.0% in 13 -year-old and 14 -year-old plantations, respectively), probably due to their close age, suggesting that age may not have effect on merchantability of the species. Mean crown diameter was higher in 14 -year-old stand (mean: 8.07 m; range 3.6 – 11.5 m) compared to 13 -year-old (mean: 5.17 m; range: 1.5 – 8.5 m).

Tree DBH distribution in *N. diderrichii* plantations followed a normal distribution curve (Figure 4a). A high percentage (37.1%) of the trees were found within 15.1 – 20 cm DBH class, followed by trees within 20.1 to 25.0 DBH class (24.7%), while only few trees were found within small (4.3%) and large (4.3%) DBH classes (Figure 4a). Tree height distribution also follows a normal distribution pattern. The majority of the trees (51.1%) fell within the height class of 15.1 - 20 m, followed by 22.0% of trees in 10.1 m – 15 m height class while the lowest percentage of trees (2.7%) were found within the height class of 25.0 m (Figure 4b).

Stand density in *N. diderrichii* plantation was generally low, with 14 -year-old stand having lower number of trees per hectare (mean: 283) than 13 -year-old plantation (mean: 426). Mean stand basal area was 12.0 m^2/ha and 12.1 m^2/ha for 14 -year-old and 13 -year-old plantations, respectively while mean total volume production was 195.8 m^3/ha 14 years plantation and 118.4 m^3/ha for 13 years stand (Table 2). Mean AGB production varied from 187.0 t/ha (range: 116.4 – 199.5 t/ha) and 214.6 t/ha (range: 191.5 - 247.7 t/ha) in 13 -year-old and 14 -year-old *N. diderrichii* plantations, respectively while mean carbon storage varied from 93.5 t/ha (range 38.2 t/ha - 114.8 t/ha) to 107.3 t/ha (range: 95.7 - 123.9 t/ha) in 13 to 14 years plantations, respectively (Table 2).

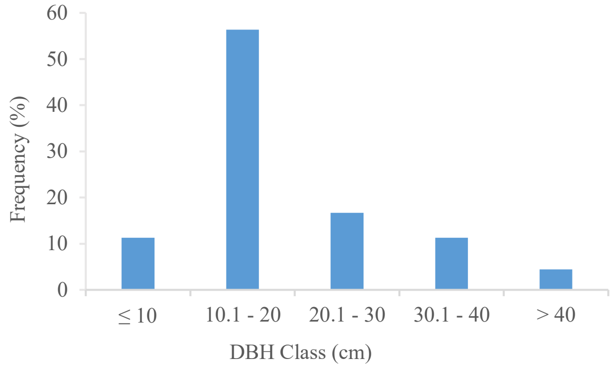

Figure 2a. DBH distribution of trees in *T. ivorensis* plantations in the study area

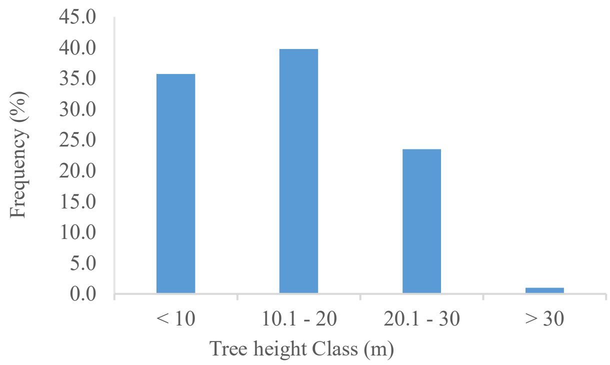

Figure 2b. Tree height distribution in *T. ivorensis* plantations in the study area

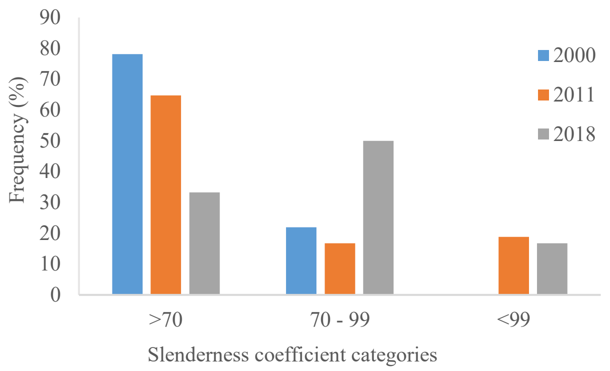

Figure 3. Slenderness Coefficient (SLC) for *T. ivorensis* trees in the study area

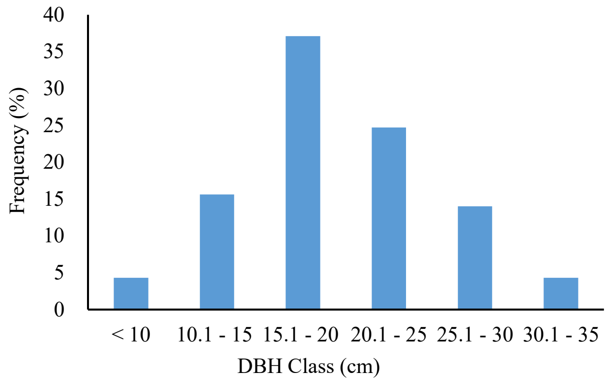

Figure 4a. DBH distribution of trees in N. *diderrichii* plantations in the study area

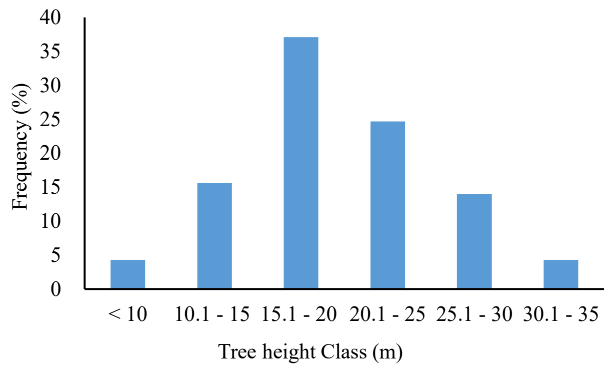

Figure 4b. Tree total height distribution in *N. diderrichii* plantations in the study area

The majority of the *N. diderrichii* trees were classified within moderate SLC category, going by the 41.5% and 48.1% of trees in this category in the 14 -year-old and 13 -year-old plantations, respectively (Figure 5). There were more trees within low SLC category in 14 -year-old plantation (35.8%) compared to 13 -year-old stand (24.5%). Trees with high SLC accounted for 34.0% and 15.1% of trees in 14 -year-old and 13 -year-old plantations, respectively (Figure 5).

The comparison of the SLC of the two species (Figure 6) suggests that *T. ivorensis* trees are more stable than *N. diderrichii* trees. This is based on the higher percentage of *T. ivorensis* trees (over 60%) found within the low SLC category compared with *N. diderrichii* trees with about 20% of its trees in this category (Figure 6). *N. diderrichii* plantations had more trees in the moderate and high SLC categories than *T. ivorensis* plantations.

3.1. Relationship between plantation age and tree growth characteristics

The relationship between tree growth characteristics for the two tree species is presented in Table 3. There was generally a positive, moderate or weak relationship between age and most growth variables (e.g. DBH, total height, crown diameter, AGB and carbon stock) while a low and negative relationship was observed between age and tree density and crown length. This implies that as the tree increases in age, most growth characteristics increases while for stand density and crown length, the reverse is the case. This agrees with the reports of some research works on the growth characteristics and management scenarios of some plantation tree species in Southwest, Nigeria (Onyekwelu et al., 2003; Onilude et al., 2017).

Table 2. Growth and yield characteristics of *N. diderrichii* plantations in the study area

	Plantation year/age							
	2010 (14 years)				2011 (13 years)			
Variables	Mean	Min	Max	SEE	Mean	Min	Max	SEE
DBH (cm)	22.4	7	33.3	0.88	18.3	6.5	33.6	0.44
Mht (m)	13.7	4.1	21.1	0.50	12.7	5.4	19.6	0.27
Tht (m)	17.8	7	26.5	0.55	16.5	5.5	27.9	0.34
CD (m)	8.1	3.6	11.5	0.24	5.2	1.5	8.5	0.11
Stand density/ ha	283	240	304	-	426	368	480	-
Mean BA (m^2/ha)	12.0	11.5	12.7	0.00	12.1	8.5	16.8	0.00
Mean Mvol (m^3/ha)	152.7	137.0	176.5	0.04	118.4	92.84	162.9	0.02
Mean Tvol (m^3/ha)	238.4	174.7	245.0	0.06	202.8	106.2	209.4	0.02
Mean AGB (t/ha)	214.6	191.5	247.7	0.06	187.0	116.4	199.5	0.02
Mean Cs (t/ha)	107.3	95.7	123.9	0.03	93.5	38.2	114.8	0.01

Min – Minimum; Max – Maximum; SEE – Standard Error of Estimate; DBH – Diameter at breast height; Mht – Merchantable height; Tht – Total height, CD – Crown diameter; BA – Basal area; Mvol – Merchantable volume; Tvol – Total volume; AGB – Above ground biomass; Cs – Carbon sequestered

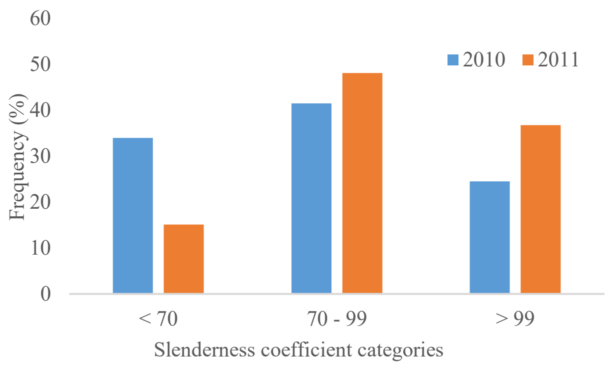

Figure 5. Slenderness Coefficient (SLC) for N. *diderrichii* trees in the study area

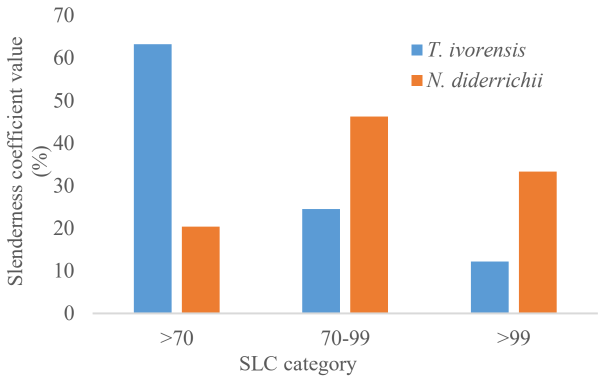

Figure 6. Slenderness Coefficient (SLC) for *T. ivorensis* and *N. diderrichii* trees in the study area

The result of the one way analysis and the T-test results were presented in Table 4 and 5, respectively. The result showed that DBH (F = 223.003, P < 0.05), tree height (F = 222.5, P < 0.05) and above ground biomass (F = 300.7, P < 0.05) have significant variation across the age classes for *T. ivorensis* (Table 4). However, levene homogeneity test for equal variances was violated, then Games-Howell (adjust for unequal variance), an improved version of Tukey method was adopted for the post hoc. Robust test of equality of means confirmed that all the growth variables tested differed significantly (Table 3). Post hoc test revealed that all pairwise differences were significant across the ages. The 24- year old stands had the highest DBH, followed by 13- year old and then, the 6-year old. The result of T-test conducted for *N. diderrichii* revealed that there were highly significant difference for DBH (t = 4.12, df = 79.22, P < 0.05) and AGB (t = 5.63, df = 69.59, P < 0.05) while difference in tree height (t = 2.14, df = 184, P > 0.05) was not significant across the 13 and 14 years old species (Table 5).

Table 3. Correlation relationship between tree age and other growth variables

	T. ivorensis			*N. diderrichii*		Combined	
Variables	24 years	13 years	6 years	14 years	13 years	*T. ivorensis*	*N. diderrichii*
Tree no	-0.30	-0.23	-0.15	-0.07	-0.22	-0.12	-0.13
DBH	0.32	0.12	0.05	0.08	0.21	0.06	0.16
Tht	0.08	0.10	0.31	0.36	0.25	0.03	0.18
BA	0.34	0.11	0.04	0.46	0.24	0.04	0.19
Tvol	0.42	0.16	0.44	0.15	0.19	0.19	0.22
Mvol	0.60	0.21	0.49	0.36	0.22	0.31	0.25
CD	0.44	0.22	0.01	0.14	0.16	-0.10	0.16
CL	-0.24	-0.15	-0.26	-0.11	-0.22	0.04	0.1
AGB	0.42	0.16	0.45	0.31	0.18	0.02	0.22
Cs	0.42	0.16	0.45	0.31	0.18	0.02	0.22

DBH- Diameter at breast height, Tht- Total height, BA- Basal area, Tvol- Total volume, Mvol- Merchantable volume, CD- Crown diameter, CL- Crown length, AGB- Above ground biomass, Cs- Carbon stock

Table 4. One-way ANOVA and tests of equality of means (Welch and Brown-Forsythe) between the growth variables of *T. ivorensis* across the age classes (age 6, 13 & 24)

Tree	GR	SV	SS	DF	MS	F	Sig.	Welch Statistics (sig.)	Brown-Forsythe Statistics (sig.)
T. ivorensis	DBH	Between Groups	14713.3	2	7356.7	223.0	0.00*	132.76 (p<0.05)	131.78 (p<0.05)
		Within Groups	6630.8	201	33.0				
		Total	21344.1	203					
	TH	Between Groups	10778.7	2	5389.3	222.5	0.00*	271.89 (p<0.05)	184.93 (p<0.05)
		Within Groups	4869.6	201	24.2				
		Total	15648.2	203					
	AGB	Between Groups	30.3	2	15.1	300.7	0.00*	101.33 (p<0.05)	116.75 (p<0.05)
		Within Groups	10.1	201	0.050				
		Total	40.4	203					

GR- Growth variables, SS- Sum of square, DF- degree of freedom, MS- Mean square, F- F-value, Sig- P-value, *- significant, DBH- diameter at breast height, TH- Tree height, AGB- Above ground biomass

Table 5. Independent sample T-test between growth variables of *N. diderrichii* across the age classes (age 13 and 14)

				Equal variances assumed	Equal variances not assumed
N. diderrichii	DBH	Levene test for equality of variances	F	6.552	
			Sig.	0.011	
		Test for equality of means	t	4.55	4.12
			df	184	79.22
			Sig. (2-tailed)	0.00	0.00
	TH	Levene test for equality of variances	F	0.16	
			Sig.	0.69	
		Test for equality of means	t	2.14	2.11
			df	184	92.53
			Sig. (2-tailed)	0.33	0.38
	AGB	Levene test for equality of variances	F	13.92	
			Sig.	0.00	
		Test for equality of means	t	6.77	5.63
			df	184	69.59
			Sig. (2-tailed)	0.00	0.00

DBH- diameter at breast height, TH- Tree height, AGB- Above ground biomass

4. Discussion

The importance of forest plantations in meeting the increasing global demand for industrial wood has been recognized (FAO, 2006; Onyekwelu, 2020). Keenan et al. (2015) opined that the decline in global natural forest area would be partly offset by the increase in forest plantation area. Timber supplies from natural forests appear to have plateaued but supplies from forest plantations are increasing and will continue to do so (Warman, 2014; Payn et al., 2015; Onyekwelu, 2020). Apart from their increasing areas, forest plantations are important due to their fast growth rate and high productivity. A comparison with the results of some previous studies indicates that our two tree species have good growth rates. Redondo-Brenes and Montagnini (2006), reported mean DBH range of 16.5 to 25.5 cm for nine native tree species plantations in Costa Rica (between 12 and 13 years old), which are comparable with the DBH of 13- and 14-years *N. diderrichii* and *T. ivorensis* plantations in this study. A 15-year-old N. *diderrichii* plantation in Nigeria had mean DBH of 19.0 cm (Onyekwelu, 2007). The maximum DBH of 27.3 cm for a 14 -year-oldclonal *Tectona gradis* plantations (Wirabuana et al., 2022) is lower than the maximum DBH of 33.3 cm and 37.8 cm for the 13- and 14-year-old *T. ivorensis* and *N. diderrichii* plantations, respectively. 13- and 14-years *Gmelina arborea* plantations in Nigeria had high maximum DBH of 39.8 cm and 48.5 cm, respectively (Onyekwelu, 2004; Onyekwelu et al., 2006), which are higher than our results. Tropical forest ecosystems are usually characterized by high tree density, complex plant diversity, nutrients competition, etc, which usually leads to low DBH and tall trees (Awosusi et al., 2020). Tree diameter is an important growth characteristic that has a great role in altering the carbon sequestration potentials of the forest (Sharma et al., 2020). This study showed that density increased with increasing diameter up to DBH class of 10.1 – 20cm and then decreased with further increase in DBH, making the graph look bell-shaped for both species, revealing that DBH distribution for *T. ivorensis* and *N. diderrichii* plantations follows a normal distribution pattern. The DBH distributions suggest that both plantations are still in the active growth stage. A similar pattern was observed by Dar et al. (2017) in the coniferous and broad-leaved forests of India.

These plantations will play an important role in meeting the growing national and global wood demand, despite their lower volume productions compared to some faster growing indigenous and exotic plantation tree species (Redondo-Brenes and Montagnini, 2006; Onyekwelu et al., 2006; Baishya et al., 2009). The lower stand volumes in this study compared to above-mentioned past studies may be explained by the low tree density in the plantations. Considering the initial planting density of 1100 trees per hectare, the current density in *N. diderrichii* (range: 240 to 480 trees ha^{-1} depending on age) and *T. ivorensis* (range: 128 to 752 trees ha^{-1} depending on age) plantations are rather low. Since the stand history is not available, the possible explanation for the low density could be planting failure and lack of beating-up, mortality due to competition and ageing, thinning and inadequate management practices. The decreasing trend of tree density with an increase in age, especially in *T. ivorensis* plantations, is expected and may be attributed to mortality, competition and anthropogenic interferences. All the growth variables differed significantly across all the age classes for the two tree species except in tree height for *N. diderrichii.* The growth pattern for the two species can be regarded as similar as DBH and AGB varied with age significantly. This growth pattern is related to the tropical forest type where diameter expansion and biomass increment continues, and vertical growth stabilize when canopy closure is achieved. This supports the reports of Chave et al. (2014) and Poorter et al. (2015) that DBH and AGB serves as sensitive indicators for determining tree volume and carbon stocks.

Forest biomass and carbon assessment are very important for national development planning as well as scientific studies of forest ecosystem productivity and carbon budget (Ajayi and Adie, 2018; Awosusi et al., 2020). The potentials of a forest to sequester carbon will influence the future balance of global carbon flux. This potential is largely determined by the rate of carbon sequestration occurring in the forest. Research workers agree that tropical plantation forests can produce up to 3–10 times more biomass than natural forests (Evans, 1999; Evans and Turnbull, 2004; Onyekwelu et al., 2006; Onyekwelu, 2020). For example, the above-ground biomass production of a natural forest in the humid tropics of India was 323.9 Mg ha^{-1} while that of a plantation forest in the same region was 406.4 Mg ha^{-1} (Baishya et al., 2009). Onyekwelu (2020), reviewed some published literature and observed that tropical forest plantation tree species (e.g. *Eucalyptus* spp., *Acacia* spp., *G. arborea, Pinus* spp., etc) can produce mean annual volume ranking of between 30 and 55m^3 $ha^{-1}yr^{-1}$, which could be higher if genetically improved planting stocks are used. This high productivity has been attributed to adequate site preparation, pioneer-type characteristics of plantation tree species and their genetic make-up, intensive management of forest plantations, and the use of improved planting material from tree breeding programmes (Onyekwelu, 2020). Results revealed that our plantations produced volume that is comparable or higher than some published results on forest plantations (Petit and Montagnini, 2004; Onyekwelu, 2007; Wirabuana et al., 2022). The amount of AGB and carbon stock in *N. diderrichii* and *T. ivorensis* stands in this study is a testament to the two species are candidates for carbon sequestration and climate change mitigation. The results suggest that *N. diderrichii* has capacity for higher productivity than *T. ivorensis* plantations judging from the biomass and carbon of 13- and 14-years old plantations of the two species. The mean stand biomass production of 187.0 t ha^{-1} by 13 year old *N. diderrichii* plantation in this study is lower than the 220.0 t/ha for 13 years *G. arborea* plantation in Nigeria (Onyekweu, 2004) but higher than the 126.25 t/ha for 15-year-old *N. diderrichii* plantation in Nigeria (Onyekwelu, 2007). *Pinus roxburghii* plantations in Daman Hill, Nepal produced higher biomass (426.16 t ha^{-1} to 434.68 t ha^{-1}) and carbon stock (200.32 t ha^{-1} to 204.30 t ha^{-1}) (Ghimire and Lamichhane, 2023) than the two species in this study.

This fortifies the need to produce quality timber from forest plantations. Among other requirements, the tree stem for good quality timber should be cylindrical, knot free, have high merchantability and high stability. Slenderness coefficient (SLC), which is the ratio of total height of a tree to its DBH, is used as a measure of the stability of a tree against wind throw (Onilude and Adesoye, 2007). Low SLC value indicates a high resistance to wind throw (good stand stability) while high SLC shows low resistance (Adeyemi and Ugo-Mbonu, 2017). Our results revealed that 63.3% and 20.4% of trees in *T. ivorensis and N. diderrichii* plantations, respectively have low SLC values (< 70), 24.5% and 46.3% of the two species were within the moderate SLC category while 12.2% and 33.3% were observed in high SLC category. This implies that *T. ivorensis* trees have better stability and may be able to withstand wind throw more than *N. diderrichii* trees. Results from available literature suggest that *T. ivorensis* trees have similar or better stability than trees in natural and plantation forests (Ige et al., 2019; Oladoye et al., 2020; Ige and Komolafe, 2022). Trees in IITA natural forest and Omo biosphere reserve have mean SLC of 93.14% and 79.4%, respectively (Oladoye et al., 2020; Ige and Komolafe, 2022), which are lower than the SLC of 63.3% and 20.4% of trees *T. ivorensis and N. diderrichii* plantations, respectively. Comparing our results with those of Ige et al. (2019), it is evident that *T. ivorensis* trees are generally more stable than *G. arborea* trees while *G. arborea* trees are more stable than *N. diderrichii* trees, The SLC results could also be used as a guide during thinning operations. For example, since 12.2% and 33.3% of the trees in *T. ivorensis and N. diderrichii* stands in this study have high SLC and may thus be susceptible to wind and storm throw, thinning operations should first target their removal, especially those with poor stem form, irrespective of their position in the forest canopy.

The high merchantability of *T. ivorensis* and *N. diderrichii* trees is an indication of their good timber quality potential. Onyekwelu et al. (2003) defined merchantable height as the vertical distance from the ground to the lowest complete whorl of living branches that are part of the crown biomass, implying that a high percentage of the tree bole that constitutes the merchantable height is branch-free. Thus, the implication of the approximately 66% and 82% bole and volume merchantability of *I. ivorensis* and *N. diderrichii* trees is that over 60% of the bole of each species are branch free and will produce high quality timber at harvest. The high merchantability of the two species could be inherent and may be attributed to the close planting spacing (3m x 3m) used in establishing their plantations, which encouraged low self-pruning. Our results also indicated that age may not have an effect on merchantability of the two tree species.

5. Conclusion

This study has provided information on growth characteristics, stand productivity, biomass and carbon storage in *T. ivorensis* and *N. diderrichii* age series plantations at FRIN. Compared to the growth of some plantation tree species, *T. ivorensis* and *N. diderrichii* trees have a good growth rate. About 63.3% and 20.4% of trees in *T. ivorensis* and *N. diderrichii* plantations had low slenderness coefficient, indicating that *T. ivorensis* trees have better stability and thus may be able to withstand wind throw more than *N. diderrichii* trees. Merchantability was high and similar in trees of the two species (66.5 - 81.4% in *T. ivorensis* and 77.0 - 77.2% in *N. diderrichiii*). The high merchantability of *T. ivorensis* and *N. diderrichii* trees is an indication of their good timber quality potential.

The plantations of the two species produced volumes that are comparable or higher than some published results on forest plantations. *Nauclea diderrichii* plantations have the capacity for higher biomass and carbon production compared to *T. ivorensis* plantations. The amount of biomass and carbon stock in *N. diderrichii* and *T. ivorensis* plantations is a testament to the fact that they are candidates for carbon sequestration and climate change mitigation. Thus, the plantations will play an important role in meeting the growing national and global wood demand. The high productivity of the plantations can be attributed to site preparation, pioneer-type characteristics of plantation tree species, genetic make-up, intensive management and the use of improved planting material.

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