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Original Article

Enrichment Planting to Supplement Natural Regeneration of Valuable Timber Resources and African Blackwood in a Community-Managed Forest of Tanzanian Miombo Woodland

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ABSTRACT

African Blackwood (Dalbergia melanoxylon), locally known as Mpingo in Swahili, is a tree species of critical importance in Tanzania, particularly for crafting woodwind instruments such as clarinets and oboes. However, its natural population is declining due to the imbalance between its slow growth rate and high industrial demand for timber. While natural regeneration remains essential for sustaining this species, planting offers a strategic method to supplement resources. Enrichment planting in forest gaps presents a promising approach to integrating conservation with community-based forestry. This study aimed to develop an enrichment planting method to supplement the natural regeneration of African Blackwood (ABW) in local forests. A 1.5-ha permanent plot was established in a community forest, and 1,503 nursery-raised seedlings (aged over six months) were transplanted at a spacing of 2 m × 2 m. Growth and survival were monitored over five years. Results showed a survival rate of approximately 62% after five years, with a maximum seedling height of 320 cm. The observed survival and growth performance were moderate compared to other Dalbergia species' enrichment planting experiments in monoculture plantations. Growth performance varied spatially, with significant correlations between seedling growth and environmental factors such as soil pH and vegetation structure. These findings demonstrate that enrichment planting holds the potential for sustainable ABW resource conservation in natural forests. Although further long-term monitoring is necessary to evaluate its effectiveness fully, this approach offers a viable strategy for enhancing tree resources and biodiversity in community-managed forests while supporting local development and conservation goals.

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INTRODUCTION

Dalbergia melanoxylon, commonly known as African Blackwood (hereafter referred to as ABW), is widely distributed across sub-Saharan African countries, particularly in regions such as Tanzania and Mozambique (Cunningham, 2016). Known as "Mpingo" in Swahili and designated as Tanzania's national tree, ABW is a prominent component of the country's semi-deciduous Miombo woodlands, as well as coastal woodlands and wooded grasslands (Sacandé *et al*., 2007). In Tanzanian natural forests, ABW coexists with other local species such as *Acacia nigrescens*, *Afzelia quanzensis*, *Pterocarpus angolensis* and *Combretum* spp. (Nakai *et al*., 2019). It thrives under diverse environmental conditions and is found in various soil types (Nakai *et al*., 2019; Mariki, & Wills, 2014). ABW typically grows as a multi-stemmed tree with an irregularly shaped crown, reaching an average height of 5–7 meters and a diameter at breast height (DBH) of less than 38 cm (Sacandé *et al*., 2007; Lovett, 1987; Bryce, 1967). It takes approximately 70–100 years to reach a harvestable size of 24 cm DBH, as regulated in Tanzania, and grows in clusters with a population density of 9–90 trees per hectare (Gregory *et al*., 1999; Mariki, & Wills, 2014; Opulukwa *et al*., 2002; Nakai *et al*., 2019; Nyomora *et al*., 2021).

The demand for ABW timber is driven primarily by the musical instrument industry, particularly for woodwind instruments (Yamaha, & JICA, 2019; Nakai, 2020). Intensive harvesting for this purpose has raised significant concerns about its sustainability. Large-scale logging began during the early 20th century under German colonial rule in Tanzania (Ball *et al.*, 1998). Today, processed ABW timber is highly valuable, fetching prices of 14,000–20,000 USD per cubic meter (Cunningham, 2015; Jenkins *et al*., 2012). However, only about 9% of the harvested timber is usable for musical instruments, leading to extremely low yields compared to other hardwoods (Gregory *et al*., 1999). This imbalance between the slow growth rate and intensive harvesting has significantly reduced ABW's standing volume in local forests. Consequently, ABW has been classified as "Near Threatened" on the IUCN Red List since 1998 (IUCN, 2024), and its trade is regulated under the CITES treaty (UNEP-WCMC, 2017).

Enrichment planting, a method involving selective planting of seedlings in existing forests, has been successfully applied to restore logged forests in Southeast Asia (Ådjers *et al*., 1995; Hector *et al*., 2011). This approach promotes species restoration and biodiversity conservation without requiring large-scale land clearing. More recently, enrichment planting has been used to transition monoculture plantations into ecologically and economically beneficial forests (Marchall *et al*., 2022). The success of such programs depends on factors such as competition for resources and the growth characteristics of the species. For instance, survival rates exceeding 90% have been reported within a few years after planting (Millet *et al*., 2013), and *Dalbergia retusa* also achieved over 90% survival in Teak (*Tectona grandis*) plantations (Marchall *et al*., 2022).

To address the imbalance between ABW's slow natural growth and industrial demands, strategies

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such as enhanced natural regeneration, targeted planting, and fire management are essential. However, ABW regeneration faces challenges, including low seed viability and poor germination rates, relying primarily on root suckers (Nshubemuki, 1993; Mbuya *et al*., 1994; Washa *et al*., 2012; Washa, 2008). Both natural regeneration and artificial planting are further threatened by forest fires, highlighting the need for supplemental planting to support sustainable management.

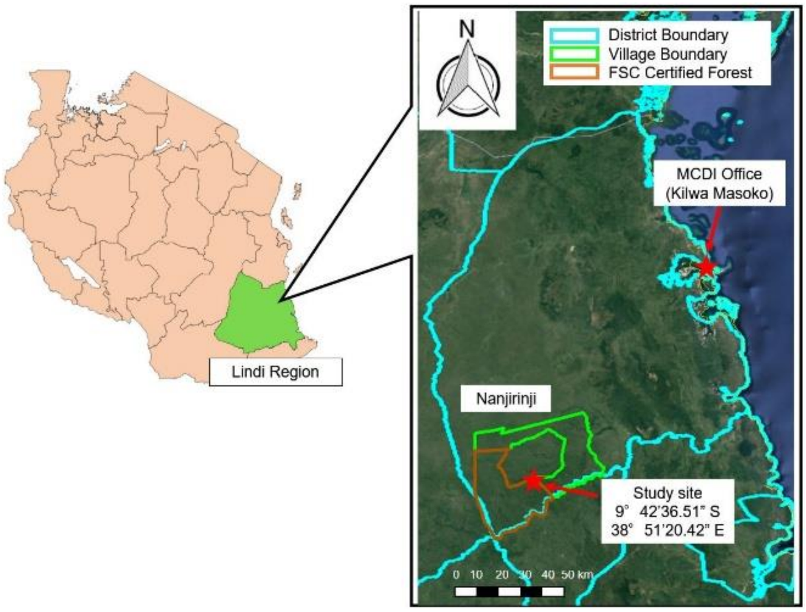
This study mainly aimed to develop an enrichment planting strategy to complement ABW's natural regeneration in Tanzanian forests. Given ABW's adaptability to diverse environments (Mariki, & Wills, 2014; Nakai *et al*., 2019), it is hypothesized that enrichment planting could enhance its growth and survival. However, the performance of ABW seedlings in the enrichment planting has not been clarified yet. The main objectives of this study were to evaluate the field performance of ABW seedlings in the natural forest as well as to specify the relevant environmental factors which affect the performance. In this study, the field performance of planted ABW seedlings was mainly evaluated based on their 5-year survival rates, height growth and the relevant environmental factors such as surrounding vegetation, soil conditions and light environment. This research also aimed to establish the best practices for ABW planting, contributing to forest conservation, community development, and the sustainable supply of timber for the musical instrument industry.

MATERIALS AND METHODS

Experimental Plot

The study site was selected in April 2017 within the community forest (VLFR: Village Land Forest Reserve) of Nanjirinji-A village, located in the southern Kilwa district, Lindi, Tanzania (*Figure 1*). The VLFR, an FSC-certified forest covering approximately 64,500 ha, has been a primary harvesting area for ABW. The certified forest is supervised according to the Participatory Forest Management program by a local non-government organization, Mpingo Conservation & Development Initiative (MCDI). A square experimental plot (100 m x 150 m; approximately 1.5 ha) was established using a GPS device (GPSMap 62s, Garmin International Inc., Kansas, USA) and a laser rangefinder (True Pulse 360, Laser Technology, Inc., Colorado, USA). The coordinates of the four corners are listed in *Table 1*.

Figure 1: Geographic Map of the Study Site (Map of Tanzania was Powered by Bing, Microsoft Open Street map)



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District Boundary was adapted from the World Bank https://energydata.info/dataset/tanzania-region-district-boundary-2012 [Updated on July 23, 2024]. Village Boundary and FSC Certified Forest area were adapted from MCDI.)

Table 1: Coordinates and Elevations of Four Corners at the Plot

Corner No.	Latitude	Longitude	Elevation (m)
Corner-1	9°42'36.51"S	38°51'20.42"E	271
Corner-2	9°42'40.44"S	38°51'23.11"E	271
Corner-3	9°42'38.55"S	38°51'25.48"E	273
Corner-4	9°42'34.35"S	38°51'22.96"E	270

Vegetation Structure and Soil Conditions

All living trees within the plot were measured and identified prior to planting, following the methodology from a previous study (Nakai *et al*., 2019). Two surveys were conducted: the initial survey in July 2017, and a 5-year monitoring survey in July 2023. Trees with a diameter at breast height (DBH, measured at 1.3 m above the ground) greater than 24 cm were tagged, and their DBH was measured using a diameter tape. For multi-stemmed trees, the largest stem was used to determine DBH. Tree heights were measured using a laser rangefinder. Each tree was identified by its local species name, and scientific names were confirmed through cross-reference with previous survey reports (Makonda, & Ruffo, 2011) (*Table 2*). The basal area (G) of each tree was calculated using the following equation (1):

$$G = \sum_{k=1}^{n} \left[\pi \left(\frac{D_k}{2}\right)^2 \right] \qquad (1)$$

where D_k represents the DBH of each stem, and k is the stem index. For multi-stemmed trees, the DBH values of all stems were summed to calculate G.

Tree population and basal area data were analysed for six sections that were subdivided into six 50 m x 50 m squares (A1, A2, B1, B2, C1, and C2) within the plot. The crown size of trees with a DBH greater than 24 cm was also measured. Crown dimensions were recorded manually in two directions: the X-axis (parallel to the line between Corners 1 and 4 in *Table 1*) and the Y-axis (parallel to the line between Corners 1 and 2). A crown projection map was created using Forest Window software (ver. 2.53, Nobori, 2000) to visualize the stand structure (*Figure 2*).

Soil samples were collected from the centre of each section (*Figure 2*) in July 2017. Two soil cores were taken at depths of 0–20 cm and 20–50 cm using a soil auger. Soil pH (H_2O), finger soil texture and colour were evaluated. Soil pH (H_2O) was measured with a glass electrode pH meter (D-51, HORIBA, Kyoto, Japan) using a 1:2.5 ratio of soil to distilled water (Nakai *et al*., 2019). Soil texture was determined by manual testing following the USDA system, and colour was assessed using the Munsell soil colour chart under the sunlight (Nakai *et al*., 2019).

Table 2: Species Name List of the Representative Trees Found in the Plot

Local Name	Scientific Name	Family
Mpingo	*Dalbergia melanoxylon*	Fabaceae
Kingonogo	*Combretum* spp.	Combretaceae
Mchuyo	*Terminalia sericea*	Combretaceae
Mjanda	*Albizia harveyi*	Fabaceae
Mlondondo	*Xeroderris stuhlmannii*	Fabaceae
Mninga jangwa	*Pterocarpus angolensis*	Fabaceae
Msenjele	*Acacia nigrescens*	Fabaceae
Msolo	*Pseudolachnostylis maprouneifolia*	Phyllanthaceae
Mukwaju	*Tamarindus indica*	Fabaceae

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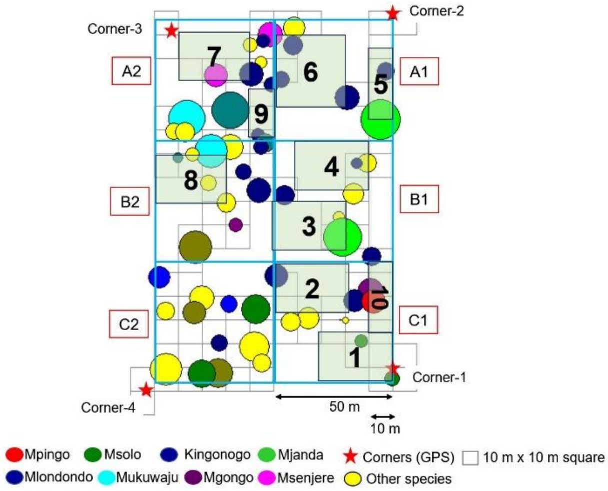
Figure 2: Crown Projection Map for the Standing Trees (only the trees over 24 cm DBH), and the Locations of all Sections and Sub-plots



The sections were indicated as the numbers in red-coloured boxes and the sub-plots designated as planting points were indicated as the black-bold numbers in grey-coloured boxes.

Preparation for ABW Seedlings and Planting

A total of 1,503 ABW seedlings were prepared in a nursery constructed in Nanjirinji-A village (*Figure 3*). Approximately 3,000 seeds collected in June 2017 from mature ABW trees in the VLFR area were propagated. Seeds were initially sown in shaded seedbeds and transplanted into plastic bottomless pots two weeks after germination. The pots were filled with a soil mixture, composed of a 1:3 ratio of sand to soil, with soil collected from the topsoil beneath mature ABW trees.

Seedlings were kept under shade and watered twice daily for 3–4 months. Two weeks before planting, the seedlings were acclimated by reducing watering frequency and gradually exposing them to sunlight (hardening) (*Figure 3*). The surviving and healthy 1,503 seedlings (over 10 cm in height) were transplanted onto the plot between December 2017 and April 2018. The initial spacing was 2 m x 2 m, and 10 sub-plots were designated as planting points based on the crown projection map (*Figure 2*). In section C2, no seedlings were planted due to the presence of bamboo shrubs.

Firebreaks were established by clearing weeds within 10 m of the site boundary. Early burning (Khatun *et al*., 2017) was conducted twice at the end of the rainy season (June and July 2017) to mitigate wildfire risk. After planting, only spot weeding was conducted at the beginning of each dry season, and no fertilizers, pesticides, or soil amendments were used.

Figure 3: ABW Seedlings at the Village Nursery, left: Germinated Seedlings at a Seedbed; right: Raised Seedlings Under the Hardening Process.

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Light Environment

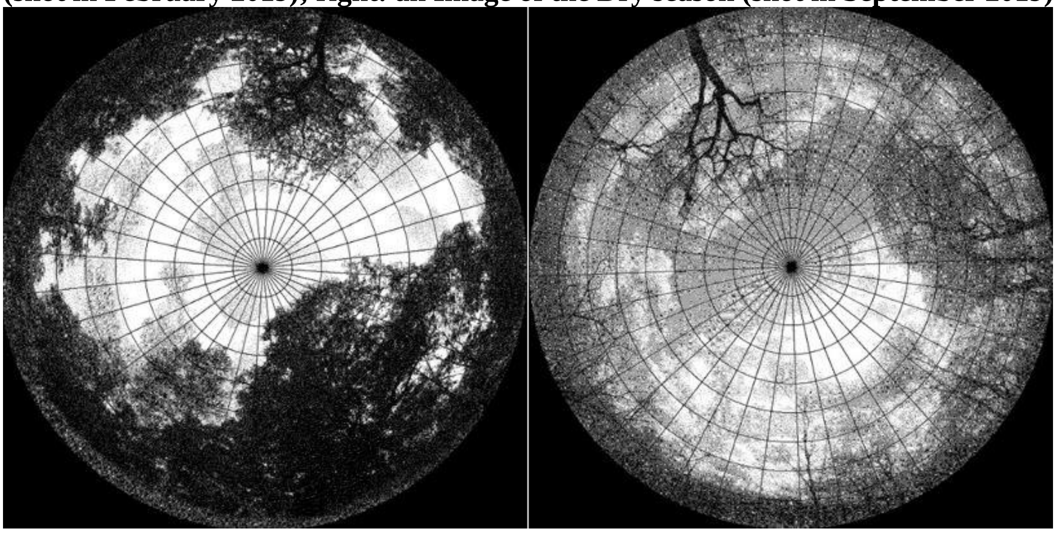
The light environment was assessed according to the parameters of canopy openness using hemispherical photographs. The canopy openness was evaluated only to understand the average light condition of each sub-plot therefore, the openness was only obtained from each centre of the sub-plot (*Figure 2*). Hemispherical photographs were taken at the centre of each sub-plot using a 360° camera (RICOH THETA S, Ricoh Company Ltd., Tokyo, Japan) mounted at a height of 1.3 m above the ground. The camera was horizontally fixed during shooting, and images were taken twice per shooting session. GPS coordinates were recorded at each shooting location (GPS Map 62s, Garmin International Inc., Kansas, USA). Canopy openness was analysed using Gap Light Analyzer (GLA), a Windows-based software application for importing, displaying, and analysing digital hemispherical canopy photographs (Frazer *et al*., 1999). Since the camera used equirectangular projection, images were converted to equidistant projection using Paint. NET (Sasaki *et al*., 2017). The full-colour photographs imported into GLA were converted to threshold images, and canopy openness was calculated for the area above 1.3 m by analyzing the proportion of white in the image. Canopy openness was measured in both the rainy (February 2019) and dry (September 2019) seasons (*Figure 4*).

Since the site is located in semi-deciduous miombo woodland, the difference (ΔC) between rainy season openness (C_R) and dry season openness (C_D) was estimated as the leaf-covered area. Using the openness values, the Leaf Area Index (LAI) was calculated using the following equation (2) (Norman, & Campbell, 1989):

$$\mathrm{LAI} = -\frac{1}{\Delta C}\ln C_R \qquad (2)$$

where C_R is the canopy openness in the rainy season, and ΔC (C_R-C_D) is equal to the leaf area projected onto a horizontal plane in this study. LAI is directly related to the indicator of canopy photosynthesis and evapotranspiration (Running, 1984; Running, & Coughlan, 1988). In this study, the LAI was only used as an indicator to understand the leaf area in the forest. The measured canopy openness and the LAI at each sub-plot were aggregated as average values at the section level.

Figure 4: The Threshold Hemispherical Images of Sub-plot 8, left: an Image of the Rainy Season (shot in February 2019); right: an Image of the Dry season (shot in September 2019)



Periodical Monitoring for Seedling Growth

Seedling survival and growth performance were monitored periodically for one year (February 2019) and five years (December 2023) after the planting. Survival rates were calculated as the ratio of counted surviving seedlings to the total planted per sub-plot. Heights were measured from the ground to the tallest living apex. Average height and survival rates were aggregated at the section level. In Tanzanian forests, fires

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significantly impact young ABW seedlings with stems under 1 meter, though their root systems often survive underground (Ball *et al*., 1998). The height growth in this study was considered as the main indicator to understanding both seedling growth and environmental conditions.

Data Analysis

Given the experimental plot size of 1.5 ha and the small sub-plot structure, the growth performance data obtained from each sub-plot might exhibit spatial dependence. Therefore, a two-step data analysis was conducted to simultaneously evaluate differences in growth performance between sub-plots and assess the relationships between growth performance and environmental factors across the plot.

First, to identify significant statistical differences in growth performance, data on average seedling height and vegetation structure (e.g., average DBH and tree height for standing trees in each section) were statistically compared between sections using the Kruskal-Wallis test. As a post hoc analysis, the Steel-Dwass test was performed at a 1% significance level to identify specific section-wise differences (BellCurve for Excel, Social Survey Research Information Co., Ltd., Tokyo, Japan).

Second, to evaluate the spatial dependence of seedling growth performance and the effects of environmental factors on relative growth rates (RGR), a series of spatial analyses were conducted, including Moran's I and a Spatial Autoregressive (SAR) model (Kissling, & Carl, 2008; Lou *et al*., 2016). These analyses were applied only to the planted sections (A1, A2, B1, B2, and C1). Python (version 3.12.0) was used for the spatial analyses, with libraries such as pysal, numpy, pandas, and matplotlib. Spatial weight matrices and Moran's I were generated using libpysal and esda. SAR modelling was performed with the spreg module. For data preparation, RGR was calculated using the following equation (3):

$$\mathrm{RGR} = \frac{\ln(H_{5y}) - \ln(H_{1y})}{t} \qquad (3)$$

where H_{5y} and H_{1y} are the heights of seedlings at 5-year and 1-year monitoring, respectively, and t is the time interval in years (4 years in this study). Environmental factors, including soil pH (0–20 cm, 20–50 cm in depth), leaf area index (LAI), canopy openness (rainy season C_R and dry season C_D) and total basal area (G), were included as explanatory variables. The G data were collected twice, as described in 2.2: the first set of G values was applied to 1-year monitoring data, and the second set to 5-year monitoring data. For the analysis, the G values were averaged to generate a static G variable.

Spatial autocorrelation of RGR was assessed using Moran's I statistics based on Queen contiguity weights. Both global and local Moran's I were calculated to identify spatial clustering patterns. Since environmental factors in each sub-plot were hypothesized to influence adjacent sub-plots due to proximity, a Spatial Lag Model (SLM) was employed to quantify the relationships between RGR and environmental variables while accounting for spatial autocorrelation. The SLM is specified as equation (4):

$$y = \rho W y + X\beta + \varepsilon \qquad (4)$$

where y represents the dependent variable (RGR), W is the spatial weights matrix, ρ is the spatial lag coefficient, X is the matrix of explanatory variables, β is the vector of regression coefficients, and ε is the error term.

The SLM outputs included coefficients of environmental factors, the spatial lag coefficient (ρ), and model diagnostics such as pseudo-R-squared, Akaike Information Criterion (AIC), and Moran's I of the residuals. Additionally, direct, indirect, and total effects of explanatory variables on RGR were computed to interpret their spatial impacts. The spatial dependence of residuals was further evaluated using Moran's I to confirm the model's suitability.

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RESULTS

Survival Rate and Growth Five Years After Planting

The survival rates and height growth are summarized in *Table 3*. The average survival rate across the site was 83.9% one year after planting, which declined to 62.1% after five years. Survival rates were consistently high (over 80%) across all sections after one year: however, significant differences emerged after five years. Section B1 (sub-plots 3 and 4) showed the lowest survival rate at 40.1%.

Table 3 also presents the average and maximum heights of surviving seedlings in each section. The average height one year after planting was approximately 27.6 cm, with no significant differences between the sections. However, by the fifth year, significant differences were observed, particularly between sections A2 and B1, and sections B1 and C1 ($p<0.01$). Maximum heights indicated substantial growth over the five years. While the average maximum height was 120 cm in one year, it increased by 200 cm in the following four years. The tallest seedlings, located in section B1, reached approximately 320 cm at the five-year mark.

Table 3: Survival and Growth for the Sections at 1-year and 5-year Monitoring

Section No.	Plot No.	No. of Planted Seedlings (trees)	Survival rate		Height of Seedlings			
					Average (mean ± SE)		Max.	
			1-year %	5-year %	1-year (cm)*	5-year (cm)*	1-year (cm)	5-year (cm)
A1	5, 6	333	83.5	57.7	30.7 ± 1.70[a]	25.8 ± 1.34[bcd]	120	140
A2	7, 9	209	84.2	83.3	30.0 ± 1.62[a]	26.1 ± 2.00[be]	71	255
B1	3, 4	364	80.2	40.1	27.0 ± 1.43[a]	37.9 ± 4.23[cf]	78	320
B2	8	136	84.6	75.0	26.0 ± 2.22[a]	40.8 ± 3.59[df]	79	200
C1	1, 2, 10	461	87.2	54.4	25.5 ± 1.08[a]	31.6 ± 2.62[de]	76	300
C2	-	-	-	-	-	-	-	-
Total		1503	-	-	-	-	-	-
Grand Average		-	83.9	62.1	27.6 ± 0.84	32.3 ± 1.22	120	320

Note. * Mean with the same letter was not significantly different (Steel-Dwass test, $p<0.01$) following the Kruskal-Wallis test.

Vegetation Structure

The total basal area (G) for all measured trees in each section is shown in *Figure 5*. Using equation 1, the total G across the site increased from approximately 5.40 m²/ha one year after planting to around 7.94 m²/ha after five years—a 2.5-fold increase over four years. Despite this growth, species composition remained largely unchanged between the one-year and five-year surveys.

The dominant species across sections was Kingonogo (*Combretum* spp.). Other notable species included Mukwaju (*Tamarindus indica*), Mjanda (*Albizia harveyi*), and Msolo (*Pseudolachnostylis maprouneifolia*). Typical Miombo woodland species, such as Mninga jangwa (*Pterocarpus angolensis*), Msenjele (*Acacia nigrescens*) and Mlondondo (*Xeroderris stuhlmannii*), which had been previously observed in the VLFR (Nakai *et al*., 2019), were also present, along with a single ABW (Mpingo, *Dalbergia melanoxylon*) tree in section C1.

Gradual increases in G were observed in sections B2 and C1, from approximately 0.76 to 0.89 m²/ha in B2 and from 0.69 to 0.74 m²/ha in C1 over the five years (*Figure 5*). *Table 4* provides further details, including tree population density, average DBH, and average height, though no significant differences were observed in these metrics across the sections or between the one-year and five-year surveys. Tree population density increased in all sections except C1, where mid-sized trees (DBH around 30 cm) likely fell during the monitoring period (*Table 4*).

Figure 5. The Total Basal Area (*G*) per Hectare by the Representative Species among the sections, (a) at 1-year and (b) at 5-year

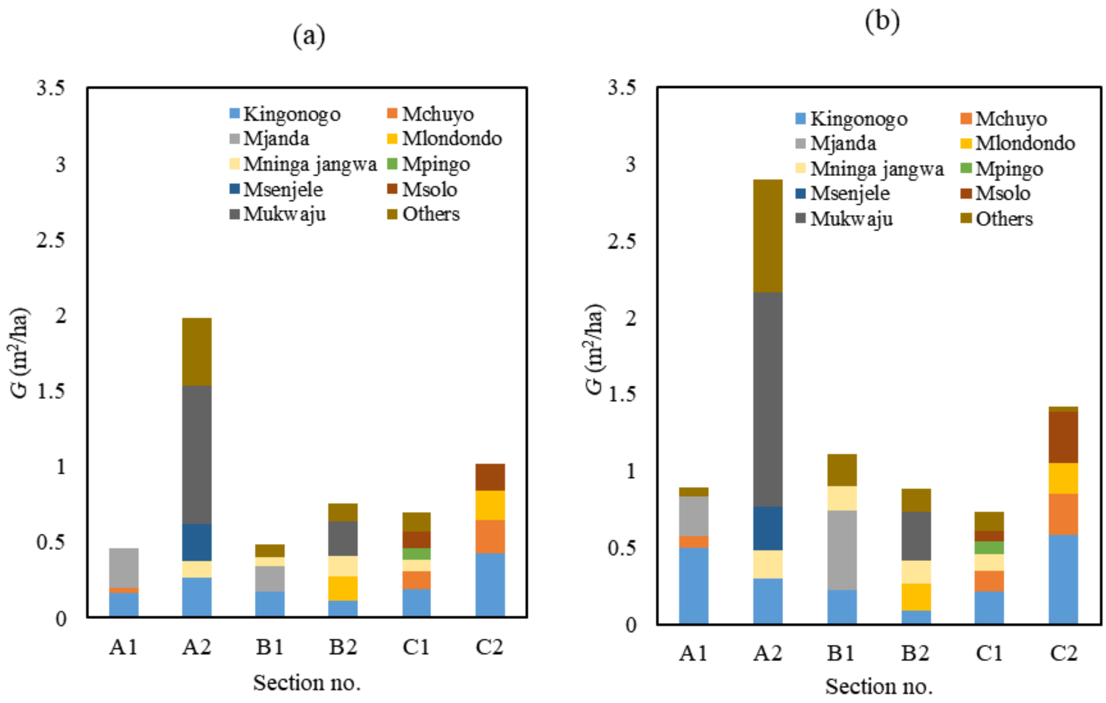

Table 4: Tree Population Density, Average DBH and Average tree Height of all the Standing Trees among the Sections (only the trees over 24 cm DBH)

Section No.	No. of tree/ha		DBH (mean ± SD)		Height (m) (mean ± SD)	
	1-year	5-year	1-year (cm)*	5-year (cm)*	1-year (m)*	5-year (m)*
A1	24.0	48.0	34.7 ± 17.72^{ae}	32.6 ± 12.51^{be}	11.9 ± 2.60^{cf}	12.2 ± 3.42^{df}
A2	68.0	88.0	40.1 ± 25.67^{ae}	43.1 ± 25.46^{be}	14.3 ± 4.46^{cf}	15.0 ± 3.64^{df}
B1	24.0	40.0	35.0 ± 11.44^{ae}	40.4 ± 14.06^{be}	12.6 ± 1.12^{cf}	11.4 ± 3.32^{df}
B2	28.0	32.0	38.7 ± 16.52^{ae}	42.1 ± 18.88^{be}	13.1 ± 3.54^{cf}	13.2 ± 4.24^{df}
C1	40.0	40.0	35.8 ± 7.00^{ae}	35.2 ± 8.37^{be}	13.0 ± 2.16^{cf}	12.7 ± 3.62^{df}
C2	52.0	68.0	37.3 ± 10.36^{ae}	36.8 ± 10.19^{be}	12.2 ± 2.63^{cf}	12.3 ± 3.35^{df}

Note. * Mean with the same letter was not significantly different (Steel-Dwass test, $p<0.01$) following the Kruskal-Wallis test.

Soil Conditions and Canopy Openness

Table 5 summarizes the soil conditions across the sections. Soil texture indicated that sand and clay are distributed across depths, with higher clay content observed at a depth of 20–50 cm. Soil colour ranged from dark reddish-brown to dark brown (Munsell 5YR–7.5YR), becoming darker along the topographic slope. Sections A2, B2, and C2, situated along the middle of a gentle convex slope, exhibited less clay content compared to sections A1, B1 and C1, which were located at the top of the slope. Soil pH ranged from slightly acidic (6.3–7.0) at the surface to the deepest layer (20–50 cm).

Canopy openness is also shown in *Table 5*. The average canopy openness during the dry season was 72.3%, while during the rainy season, it was

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37.5%. Sections A1 and A2 had lower canopy openness (around 31%) in the rainy season, while other sections exceeded 40%. Section C1 showed the highest canopy openness in both seasons, with 77.4% in the dry season and 46.1% in the rainy season. The calculated LAI averaged 2.9, consistent with semi-arid forests receiving annual rainfall of approximately 1,000 mm (Woodgate *et al.*, 2015). The lowest LAI was observed in C1 (2.5), while the highest was recorded in B2 (3.1) (*Table 5*).

Table 5. Soil Conditions and Canopy Openness Among the Sections (Grand Average Values Presented as mean ± SD). Soil Conditions Include Soil Texture, Colour, and pH (H_2O)

Section No.	Soil Conditions						Canopy Openness			
	Texture		Colour (Hue, Value/Chroma)		pH (H_2O)		C_D %	C_R %	ΔC %	Estimated LAI
	0-20 cm	20-50 cm	0-20 cm	20-50 cm	0-20 cm	20-50 cm				
A1	SC	C	5YR 3/3	5YR 3/6	6.5	6.6	70.2	31.3	38.9	3.0
A2	CL	C	5YR 3/6	5YR 3/6	6.9	6.6	71.3	31.2	40.1	2.9
B1	C	C	5YR 3/4	5YR 3/6	6.6	6.3	72.4	38.5	33.9	2.8
B2	CL	C	7.5YR 3/3	5YR 4/4	6.4	5.9	70.0	40.7	29.3	3.1
C1	C	C	5YR 4/4	5YR 3/6	6.1	6.0	77.4	46.1	31.3	2.5
C2	CL	C	7.5YR 3/2	5YR 4/3	6.8	6.4	N/A	N/A	N/A	N/A
Grand Average	SC-C	C	-	-	6.5 ± 0.28	6.3 ± 0.30	72.3 ± 3.03	37.5 ± 6.39	34.7 ± 4.68	2.9 ± 0.23

Note. Canopy openness values were obtained from the centre of each plot; averages were calculated for sections with multiple plots.

Spatial Dependence and Effects of Environmental Factors on RGR

Global spatial autocorrelation analysis revealed a statistically significant Moran's I value of 0.516 p = 0.001), indicating moderate spatial clustering of seedlings' RGR. This result justified the application of a spatially explicit modelling approach to consider the spatial dependence on the obtained data. The SLM with RGR as the dependent variable and environmental factors as explanatory variables exhibited strong overall performance, with a pseudo-R-squared value of 0.870 and a spatial pseudo-R-squared of 0.865. Additional model diagnostics, including a log-likelihood of 1841.971 and an AIC of -3667.942, supported the model's suitability.

The SLM provided insights into the direct, indirect and total effects of environmental factors on RGR as described in *Figure 6*. Soil pH at 0–20 cm depth positively influenced RGR (Direct effect: 0.73, Indirect effect: 1.76, Total effect: 2.49), while pH at 20–50 cm depth had a negative impact (Direct effect: -0.67, Indirect effect: -1.63, Total effect: -2.30). Total basal area (G) which was applied as a static value, exhibited a negative effect on RGR (Direct effect: -0.05, Indirect effect: -0.12, Total effect: -0.17), and LAI also exhibited a negative effect on RGR (Direct effect: -0.05, Indirect effect: -0.13, Total effect: -0.18). In contrast, canopy openness (C_R and C_D) had comparatively minor effects, as indicated by their lower total effect values (*Figure 6*).

The spatial lag coefficient of 0.71 confirmed that RGR in one section was significantly influenced by growth in neighbouring sections. The minimal spatial autocorrelation in the residuals (Moran's I

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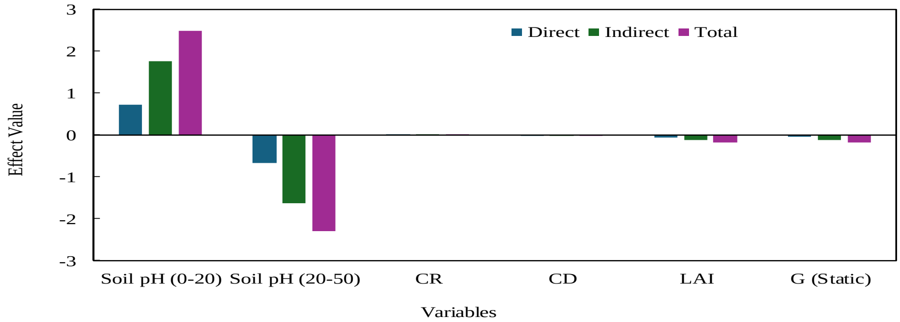
= 0.094, p = 0.001) indicated that the SLM effectively accounted for spatial dependence in the data.

Figure 6: Effect Values of Each Environmental Factor on RGR



DISCUSSION

The survival rate of ABW seedlings observed in this study (62.1% at five years, *Table 3*) was moderate compared to other enrichment planting experiments in plantation settings, where survival rates often exceed 90% over a similar timeframe (Millet *et al*., 2013; Marshall *et al*., 2022). The relatively lower survival rate in this study likely reflected the more complex environmental conditions of natural forests. Despite this, the survival rate aligns with expectations for enrichment planting in natural forest systems, where competition, disturbances, and variable site conditions inherently limit growth performance. The results suggest that the implemented planting method is a viable approach for managing ABW in community-managed natural forests.

For *Dalbergia* species in enrichment plantings, survival and growth are known as particularly sensitive to light environments. For example, *Dalbergia retusa* achieved a 97% survival rate and an average height of 180 cm after 30 months in a monoculture Teak (*Tectona grandis*) plantation in Panama (400–900 trees/ha) (Marshall *et al*., 2022). Conversely, in Vietnam, *Dalbergia bariensis* planted in a mixed-species plantation (400 trees/ha) showed a decrease in survival from 95% to 59% as canopy openness increased (Millet *et al*., 2013). These studies underscore the importance of intermediate light levels for optimal growth in *Dalbergia* species (Marshall *et al*., 2020).

However, the performance of ABW seedlings in this study suggested that, within Miombo woodland, the priority of light conditions might differ from other forest types. While light conditions influenced RGR in this study, their impact was less pronounced compared to soil factors. LAI negatively affected RGR, whereas canopy openness (both C_R and C_D) had relatively minor effects (*Figure 6*). The site, characterized as open woodland typical of Miombo woodlands' ecosystems, exhibited high canopy openness during the dry season (72.1%) and moderate openness during the rainy season (37.5%) (*Table 5*). The average height of trees at the plot was 11–15 m (considering only trees over 24 cm DBH), and most species—such as Kingonogo (*Combretum* spp.), Mninga jangwa (*Pterocarpus angolensis*), Mlondondo (*Xeroderris stuhlmannii*), and Mpingo (ABW)—are deciduous during the dry season. In this study, ABW seedlings were planted in a secondary forest within Miombo woodland, a type known to support fewer regenerating ABW individuals in denser conditions (Mbuya, 1994; Washa, 2008). A prior study in the same VLFR indicated a tree population density of about 211 trees/ha for trees over 10 cm DBH (Nakai *et al*., 2019), much lower than typical plantation densities. These characteristics likely reduce the competitive

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pressure from surrounding vegetation and, consequently, the priority of light conditions as a growth determinant. Although ABW is generally considered a light-demanding species (Orwa *et al*., 1994; Ball *et al*., 1998; Washa, 2008), its moderate growth performance in this study suggests that the light may play a less critical role in Miombo woodlands compared to denser forest types.

The SLM revealed that soil pH strongly influenced seedling growth (*Figure 6*). Soil conditions are known to influence vegetation structure and tree growth (Ilunga Muledi *et al*., 2016). The SLM results indicated contrasting effects of soil pH at different depths: positive at 0–20 cm and negative at 20–50 cm (*Figure 6*). The upper layer of soil (0–20 cm) contained higher organic matter and nutrients, as evidenced by its darker colour and higher clay content (*Table 5*). In contrast, the lower layer (20–50 cm) contained heavier clay (*Table 5*), likely with high calcium carbonate ($CaCO_3$) content, which may impede root extension. This difference suggests that ABW roots benefit from nutrient-rich upper layers but are inhibited by denser, clay-rich lower layers.

Variations in total *G* across the sections further influenced seedling growth. At the one-year mark, sections at the slope top (A1, B1, and C1) had lower *G* values compared to the mid-slope sections (A2, B2, and C2) (Figure 5a). Over five years, basal area growth in B1 increased significantly due to the growth of Mjanda (*Albizia harveyi*), even though B1 had the lowest survival rate among sections (Table 3). This potentially suggests that resource competition with mature trees has constrained ABW seedling growth in B1. Similarly, A2, which had the highest basal area due to the presence of a large Mukwaju (*Tamarindus indica*), exhibited slower seedling height growth despite a higher survival rate than B1 (*Figure 5*). The SLM indicated a negative effect of total *G* on RGR, consistent with these observations (*Figure 6*). These findings suggest that ABW growth is apparently suppressed in areas with larger, mature tree patches, reflecting its limited competitive ability in denser forests.

Topographic factors also significantly influenced seedling survival and growth. Sections at the slope top (A1, B1, and C1) showed higher seedling mortality and lower growth rates compared to mid-slope sections (A2, B2, and C2, *Table 3*). The slope-top sections were closer to a road connecting the village to the VLFR, making them more susceptible to disturbances such as wildfires, grazing, and human activities. While early burning and firebreaks effectively mitigated large-scale wildfires, localized disturbances likely affected seedling growth. Previous studies identified wildfires as a primary disturbance in reserved areas (Manyanda *et al*., 2021). Although no significant wildfire events were detected in this study (as suggested by stable basal area data, *Figure 5*), small-scale human activities may have had localized impacts.

This study highlighted the complex interplay of environmental factors, including soil conditions, vegetation structure, light environment, and topography, on the growth performance of ABW seedlings. The observed variations in survival and growth underscore the importance of tailoring enrichment planting strategies to site-specific conditions. For ABW, which is typically found in patchy clusters (Opulukwa *et al*., 2002), adaptive management practices that address resource competition and environmental variability are crucial for improving regeneration success. In Miombo woodlands, the role of light appears less critical than in other forest ecosystems, suggesting that site-specific characteristics must be carefully considered when designing planting strategies.

CONCLUSIONS

The findings of this study demonstrate the potential of enrichment planting as a supplementary approach for the resource management of ABW. While the five-year survival rate of 62.1% was lower than the high rates observed in plantation settings (e.g., >90%), it aligns with expectations for natural forest systems, where environmental variability and competition inherently limit performance. These results suggest that the implemented planting

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method is a viable strategy for ABW in community-managed natural forests.

Soil conditions, particularly pH, significantly influenced seedling growth. The positive impact of higher pH at shallower soil depths suggests that young seedlings can thrive in forest gaps, consistent with previous findings on ABW's adaptability to diverse soil types. Vegetation types, as indicated by basal area, also affected growth performance: lower survival rates were observed in slope-top sections, while slower growth occurred in middle-slope sections with large mature trees. The light environment had a partial influence, with the LAI negatively affecting growth performance. Planting sections farther from the roadside showed higher survival rates, indicating minimal impact from large-scale disturbances during the study period.

Enrichment planting holds promise not only for enhancing forest diversity but also for supplementing the natural regeneration of endangered species such as ABW. This study provides a promising foundation for expanding ABW planting efforts to support both conservation and sustainable resource management. While further long-term monitoring is needed to fully assess the effectiveness of this approach, enrichment planting shows significant potential to contribute to ABW conservation and resource management. Additionally, it offers opportunities for local community development by balancing immediate and long-term benefits through sustainable practices.

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DECLARATION OF COMPETING INTEREST

The authors declare that they have no competing interests.

DATA AVAILABILITY

Data will be made available by the corresponding author upon reasonable request.

REFERENCES

Ådjers, G., Hadengganan, S., Kuusipalo, J., Nuryanto, K., & Vesab, L. (1995). Enrichment planting of dipterocarps in logged-over secondary forests: effect of width, direction and maintenance method of planting line on selected *Shorea* species. *Forest Ecology and Management*, 73, 259–270

Ball, S. M. J., Smith, A. S., Keylock, N. S., Manoko, L., Mlay, D., Morgan, E. R., Ormand, J. R. H., & Timothy J. (1998). Tanzanian Mpingo '96 Final Report. Mpingo Conservation Project, Fauna & Flora International, Cambridge.

Bryce, J. M. (1967). The commercial Timbers of Tanzania. Forest Division, Ministry of Agriculture & Co-operatives, Moshi, Tanzania

Cunningham, A. B. (2016). Trade study of selected East African timber production species. In: *Proceedings of the Convention on International Trade in Endangered Species of Wild Fauna and Flora Seventeenth Meeting of the Conference of the Parties* (pp. 27–66). Johannesburg, South Africa.

Cunningham, A. B. (2015). More than a music tree: 4400 years of *Dalbergia melanoxylon* trade in Africa. *South African Journal of Botany*. 98: 167.

Article DOI: https://doi.org/10.37284/eajfa.8.1.2805

Frazer, G. W., Canham, C. D., & Lertzman K. P. (1999). *Gap Light Analyzer (GLA): Imaging software to extract canopy structure and gap light transmission indices from true-colour fisheye photographs, user's manual and program documentation*. Copyright © 1999: Simon Fraser University, Burnaby, British Columbia, and the Institute of Ecosystem Studies, Millbrook, New York.

Gregory, A., Ball, S. M. J., & Eziefula, U. E. (1999). *Tanzanian Mpingo 98 Full Report*. Mpingo Conservation Project, Tanzania.

Hector, A., Philipson, C., Saner, P., Chamagne, J., Dzulkifli, D., O'Brien, M., Snaddon, J. L., Ulok, P., Weilenmann, M., Reynolds, G., & Godfray, H. C. J. (2011). The Sabah Biodiversity Experiment: a long-term test of the role of tree diversity in restoring tropical forest structure and functioning. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 366(1582), 3303–3315.

Ilunga Muledi, J., Bauman, D., Drouet, T., Vleminckx, J., Jacobs, A., Lejoly, J., Meerts, P., & Shutcha, M.N. (2016). Fine-scale habitats influence tree species assemblage in a miombo forest. *Journal of Plant Ecology*, 10(6), 958–969.

Jenkins, M., Oldfield, S., Aylett, T., Jenkins, M., Oldfield, S., & Aylett, T. (2002). *International trade in African blackwood* (p. 7). Cambridge, UK: Fauna & Flora International.

Khatun, K., Corbera, E., & Ball, S. (2017). Fire is REDD+: offsetting carbon through early burning activities in south-eastern Tanzania. *Oryx*, 51(1), 43–52.

Kissling W. D., & Carl G. (2008). Spatial autocorrelation and the section of simultaneous autoregressive models. *Global Ecology and Biogeography*, 17(1), 59–71.

Lou, M., Zhang, H., Lei, X., Li, C., & Zang, H. (2016). Spatial autoregressive models for stand top and stand mean height relationship in mixed *Quercus mongolica* broadleaved natural stands of Northeast China. *Forests*, 7(2), 43.

Lovett, J. (1987). Mpingo – the African Blackwood. *Swara*, 10, 27-28.

Maconda, F. B. S, & Ruffo C. K. (2011). Species List sorted by vernacular names (common names). In: *National Forestry Resources Monitoring and Assessment of Tanzania (NAFORMA)*. Forestry and Beekeeping Division, Ministry of Natural Resources and Tourism, Dar es Salaam, Tanzania.

Manyanda, B. J., Nzunda, E. F., Mugasha, W. A., & Malimbwi, R. E. (2021). Effects of drivers and their variations on the number of stems and aboveground carbon removals in miombo woodlands of mainland Tanzania. *Carbon balance and Management*, 16(1), 16.

Mariki, A. S., & Wills, A. R. (2014). Environmental Factors Affecting Timber Quality of African Blackwood (*Dalbergia melanoxylon*). Mpingo Conservation & Development Initiative, Tanzania.

Marshall, A., McLaughlin, B. P., Zerr, C., Yanguas-Fernández, E., & Hall, J. S. (2020). Early indicators of success rehabilitating an underperforming teak (*Tectona grandis*) plantation in Panama through enrichment planting. *New Forests*, 52(3), 377–395.

Marshall, A., Nelson, C. R., & Hall, J. S. (2022). Species selection and plantation management in enrichment planting with native timber species in the Panama Canal watershed. *Frontiers in Forests and Global Change*, 5, 925877.

Mbuya, L. P., Msanga, H. P., Ruffo, C. K., Birnie, A., & Tengnas, B. O. (1994). Useful trees and shrubs for Tanzania. *Identification, propagation and management for agricultural and pastoral communities*. Regional Soil Conservation Unit, Swedish International Development Authority, Swedish Embassy, Nairobi, Kenya.

Millet, J., Tran, N., Vien Ngoc, N., Tran Thi, T., & Prat, D. (2013). Enrichment planting of native species for biodiversity conservation in a logged tree plantation in Vietnam. *New Forests*. 44, 369–383.

Nakai, K. (2020) Enhancing the potential of African Blackwood, *Dalbergia melanoxylon*, through sustainable forest utilization: a valuable tree species in Tanzanian miombo forest. Doctoral Thesis, Kyoto University, Kyoto.

Nakai, K., Ishizuka, M., Ohta, S., Timothy, J., Jasper, M., Lyatura, N. M., Shau, V., & Yoshimura T. (2019). Environmental factors and wood qualities of African blackwood, *Dalbergia melanoxylon*, in Tanzanian Miombo natural forest. *Journal of Wood Science*, 65(39), 1–11.

Nobori, Y. (2000). Forest Window. Japan Society of Forest Planning Press. p100. Tokyo.

Norman, J. M., & Campbell, G. S. (1989). Canopy structure. In: *Percy R.W., Ehleringer J., Mooney H.A., Rundel P.W. (Eds.) Plant Ecology: Field methods and Instrumentation* (pp. 301–325). Chapman & Hall, London.

Nshubemuki, L. (1993). *Dalbergia melanoxylon*: Valuable Wood from a Neglected Tree. NFT Highlights 1993-1995. Nitrogen Fixing Tree Association, Hawaii, US.

Nyomora, A. M. S., Washa, B. W., & Nnungu, S. I. (2021). Assessment of African Blackwood (*Dalbergia melanlxylon*) population structure in Kilwa District, Tanzania. *Tanzania Journal of Science*, 47(4), 1442–1449.

Opulukwa, M. J., Hamza, K. F. S., & Malende, Y. H. M. B. (2002). Inventory of *Dalbegia melanoxylon* (Mpingo) in the southern part of Tanzania: The case of Nachingwea. *African Study Monographs*, 23(1), 1–10.

Orwa, C., Mutua, A., Kindt, R., Jamnadass, R., & Simons, A. (1994). Agroforestry database: a tree species reference and selection guide version 4.0. World Agroforestry Centre ICRAF, Nairobi, KE. http://www.worldagroforestry.org/sites/treebs/treedatabases.asp. Accessed 15 Oct 2024

Running, S. W. (1984). Microclimate control of forest productivity: analysis by computer simulation of annual photosynthesis/transpiration balance in different environments. *Agricultural and Forest Meteorology*, 32 (3-4), 267–288.

Running, S. W., & Coughlan, J. C. (1988). A general model of forest ecosystem processes for regional applications I. Hydrologic balance, canopy gas exchange and primary production processes. *Ecological Modelling*, 42(2), 125–154.

Sacandé, M., Vautier, H., Sanon, M., & Schmit, L. (2007). *Dalbergia melanoxylon* Guill. & Perr (Seed Leaflet Report No. 135), University of Copenhagen, Copenhagen, Denmark.

Sasaki, T., Niwa, H., Asanami, F., & Kamada, M. (2017). Estimation of floor light conditions of a coastal pine forest using a small Unmanned Aerial Vehicle. *Journal of the Japanese Society of Revegetation Technology*, 43(1), 51–55. (in Japanese)

UNEP-WCMC (2017). Review of selected *Dalbergia* species and *Guibourtia demeusei*. UNEP-WCMC, Cambridge.

Washa, B. W. (2008). Dependence of *Dalbergia melanoxylon* natural populations on root suckers' regeneration. *Journal of African Affairs*, 24(32), 177–198.

Washa, B. W., Nyomora, A. M. S., & Lyaruu, H. M. V. (2012). Improving propagation success of *D. melanoxylon* (African Blackwood) in Tanzania (II): rooting ability of stem and root cuttings of *Dalbergia melanoxylon* (African Blackwood) in response to rooting media sterilization in Tanzania. *Tanzania Journal of Science*, 38(1), 43–53.

Woodgate, W., Jones, S. D., Suarez, L., Hill, M. J., Armston, J. D., Wilkers, P., Soto-Berelov,

Article DOI: https://doi.org/10.37284/eajfa.8.1.2805

M., Haywood, A., & Mellor A. (2015). Understanding the variability in ground-based methods for retrieving canopy openness, gap fraction, and leaf area index in diverse forest systems. *Agricultural and Forest Meteorology*, 205, 83–95.

International Union for Conservation of Nature and Natural Resources. (2024). *Dalbergia melanoxylon*. The IUCN Red List of Threatened Species. Version 2024-2 (Accessed 10 January 2025)

Yamaha Corporation, & Japan International Cooperation Agency (2019). The United Republic of Tanzania, preparatory survey on BOP business for sustainable procurement of FSC certificated wood: Final Report. Japan International Cooperation Agency, Tokyo.