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Environmental factors and wood qualities of African blackwood, *Dalbergia melanoxylon*, in Tanzanian Miombo natural forest

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Abstract
African blackwood (ABW) (*Dalbergia melanoxylon*) mainly occurs in the coastal areas of East Africa, including in Tanzania and Mozambique, and its heartwood is commonly known to be one of the most valuable materials used in the production of musical instruments. Although the heartwood is one of the most expensive timbers in the world, very low material yield has recently resulted in the significant reduction of natural individuals. This might have serious impact on local communities, because this tree is apparently the only species that can support their livelihood. Therefore, a solution to the problem is urgently needed in terms of the sustainable development of communities. In this study, we survey environmental factors (stand structure and soil properties) in the Miombo woodlands of southern Tanzania, where ABW was once widely distributed, to clarify the factors affecting growing conditions of ABW. Three community forests located in Kilwa District, Lindi, Tanzania, were selected as the survey sites, and 10–13 small plots (0.16 ha/plot) were randomly established at each site. In addition, the stem qualities of standing trees were evaluated by visual inspection rating and a non-destructive measurement of stress-wave velocity, for understanding the relationship between environmental factors and growth form. It was found that ABW was widely distributed under various environmental conditions with intensive population, and that their growth form depended on environmental factors. Since there was no significant difference of stress-wave velocities among the site, our findings suggest that the dynamic properties of ABW trees does not depend on growth conditions, which is generally influenced by various external factors. These results present important information regarding the sustainable forest management of ABW.

Keywords: *Dalbergia melanoxylon*, Musical instruments, Distribution, Environmental factors, Growth condition

Introduction

African blackwood (ABW, *Dalbergia melanoxylon*), commonly known as Mpingo in Swahili (trade name, grenadilla), is generally used in the manufacture of clarinets, oboes, bagpipes and other musical instruments. It has been traded to European countries for this purpose since the early nineteenth century [1]. ABW is valued as an appropriate material for musical instruments not only because of its exterior appearance, but also due to the precious advantages of the material. For example, the air-dried density of heartwood ranges from 1.1 to 1.3 g/cm^3 [2, 3], while the loss factor (tanδ) is lower than that of other general hardwood species [4]. Since ABW is the only species that can meet the requirements for musical instrument production, the conservation of this timber resource is vitally important for a sustainable music industry.

African blackwood is now widely distributed throughout tropical Africa, found in at least 26 sub-Saharan countries including Tanzania, Kenya, Ethiopia and Nigeria [5]. It can grow under a wide range of conditions from semi-arid, to sub-humid, to tropical lowland areas [6, 7], and occurs in deciduous woodland, coastal bushland and wooded grassland, where the soils are sufficiently moist

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[5]. ABW is frequently observed in Miombo woodland, which covers approximately 10% of the African continent [8]. Miombo woodland is a semi-deciduous formation characterized by dominant trees in the genera *Brachystegia*, *Julbernardia* and *Isoberlinia* [9–11]. It supports the livelihood of 100 million people around the area who rely on products from this distinct and unique biome [12]. In addition, ABW is an economically important tree in many African woodlands, supporting local communities.

Currently, the local NGO, Mpingo Conservation & Development Initiative (MCDI), is working for sustainable forest conservation based on a Forest Stewardship Council (FSC)-certified forest in the southern part of Tanzania, Kilwa district, Lindi. MCDI focuses on a Participatory Forest Management system (PFM), which acts as a basic legal facilitator for Reducing Emissions from Deforestation and forest Degradation, plus the sustainable management of forests, and the conservation and enhancement of forest carbon stocks (REDD+). It gives local communities control and ownership of their local forest resources, including timber, through demarcated village land forest reserves (VLFRs), which would otherwise be controlled by the government [13, 14]. Its contribution to controlling illegal logging can also lead to improved local community forestry. ABW has become one of MCDI's most important species, not only in terms of historical utilization [15–17], but also for income generation.

As mentioned above, ABW is mainly used in the musical instrument industry, although it is also used for decorative objects such as traditional carvings [15, 16, 18, 19]. The general characteristics of ABW trees have been reported: average height, 5–7 m; multi-stemmed with a bole circumference normally <120 cm; and irregularly shaped crown [5, 20]. Small trees tend to cause serious problems in the operation of sawmills due to lateral twists, deep fluting, and knots including cracks [21]. Such defects may affect the general performance of musical instruments. For example, the internal surface condition of the wood can impact acoustic attenuation in the cylindrical resonators of woodwind instruments [22]. As a result, sawmills can generate only a small amount of timber of the necessary quality, with an actual timber yield of 9% [23]. Meanwhile, intensive harvesting has induced a social concern about the sustainability of ABW resources. This inefficient utilization has made ABW one of the most highly priced timbers in the world, with a market rate of US$14,000–20,000 per m^3 [1, 24], and has threatened the species' future existence [24, 25]. In fact, ABW has been designated as "near threatened" on the IUCN (International Union for Conservation of Nature) red list since 1998 [26], and since 2017, the trade of all existing *Dalbergia* species including ABW has been restricted worldwide by the CITES (Convention on International Trade in Endangered Species of Wild Fauna and Flora) treaty [27].

The main purpose of this study is to assess the potential of the ABW tree in terms of sustainable forest utilization. The relationship between distribution and environmental factors (surrounding vegetation and soil) must be clarified before sustainability of ABW in natural forest can be achieved. Although some difficulties have currently been noted in terms of the economic feasibility of ABW [23], forest management focused on this resource could continuously contribute to the local community forest due to the economical uniqueness of the wood. Therefore, valuable ABW that meets the requirements of musical instruments should be produced effectively by controlling appropriate growth conditions.

In general, the surrounding environment, including climate factors, soil type, and surrounding vegetation, has the potential to influence tree growth. Such environmental conditions have already been studied in some locations [28–33], however, the relationship between environmental conditions and wood quality has not been yet been clarified. In this study, some environmental conditions in the natural distribution areas of ABW were compared to determine the relationship between tree growth and wood quality. Our results can contribute to establishing sustainable forest management by local communities.

Materials and methods

Survey sites

A forest survey was conducted in the southern part of Tanzania, Kilwa District, Lindi, which covers 13,347.5 km^2 and is one of Tanzania's most densely forested districts [34]. More than 150,000 ha of this area has been designated FSC-certified forest supported by MCDI, and that has principally been community forests managed by a local group. For this study, three FSC-certified community forests (Kikole, Nainokwe, and Nanjirinji) were selected as samples (Fig. 1). In each forest, 9–11 small temporary plots (0.16 ha: 40 m × 40 m) were randomly set using GPS (eTrex, Garmin International Inc., Kansas, USA) and a laser range finder (TruPulse360, Laser Technology, Inc., Colorado, USA). A total of 31 plots were set as study sites: 11 in Kikole and Nainokwe, and 9 in Nanjirinji. In this study, 2 plots without ABW trees were included at each site as references. The survey was conducted in July and December 2017.

Vegetation survey

All living trees over 10 cm DBH (diameter at breast height: 1.3 m from the ground) were measured for DBH using a diameter tape. In the case of multi-stemmed trees less than

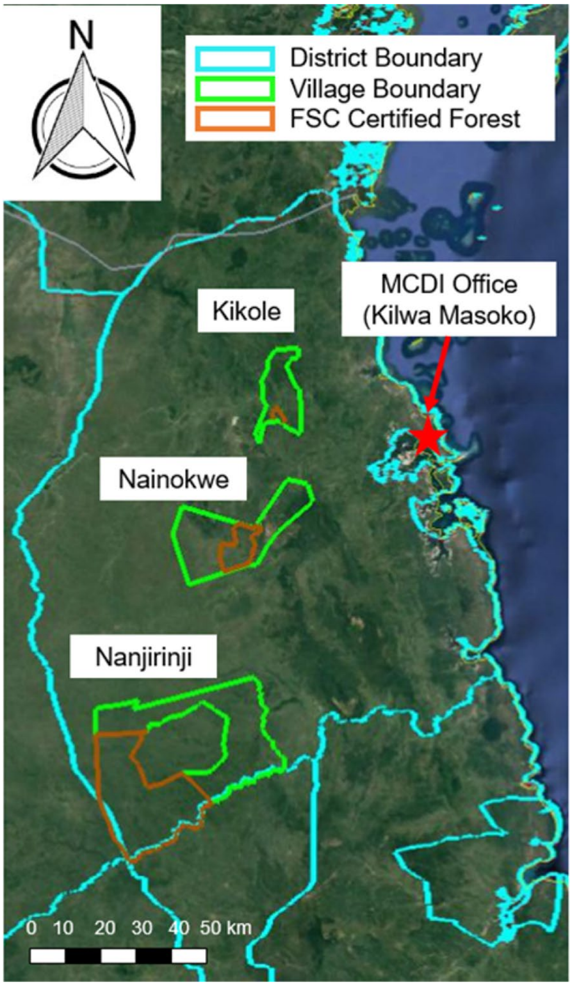

Fig. 1 Location map of the survey sites (District Boundary was adapted from The World Bank: https://energydata.info/dataset/tanzania-region-district-boundary-2012, Village Boundary and FSC Certified Forest area were adapted from MCDI: http://www.mpingoconservation.org/where-we-work/on-the-map/)

1.3 m above the ground, each stem was measured separately, and the biggest DBH stem was regarded as the individual DBH. The number of individuals was also counted in this way. Trees were tagged and classified by local species name. Each scientific name was finally identified as supplemental information referenced by previous survey reports [23, 29, 35] (Table 1). Furthermore, both tree height and branch height of ABW trees over 10 cm DBH were measured to evaluate the growth form of ABW. Basal area of each tree, G, was calculated by the following equation (Eq. 1):

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

Table 1 Local and scientific names of trees in the survey sites [24, 30, 36]

Local name	Scientific name	Family
Mpingo	*Dalbergia melanoxylon*	Fabaceae
Mhani	*Brachystegia* spp.	Fabaceae
Miombo	*Brachystegia spiciformis*	Fabaceae
Msolo	*Pseudolachnostylis maprouneifolia*	Phyllanthaceae
Mnepa	*Pteleopsis myrtifolia*	Combretaceae
Mtomoni	*Diplorhynchus condylocarpon*	Apocynaceae
Kingonogo	*Combretum* spp.	Combretaceae
Pangapanga	*Millettia stuhlmannii*	Fabaceae
Mchenga	*Julbernardia paniculata*	Fabaceae
Mtondoro	*Julbernardia paniculata*	Fabaceae
Msumari	Not identified	
Msenjele	*Acacia nigrescens*	Fabaceae
Muhungo	*Acacia robusta*	Fabaceae
Mjare	*Sterculia appendiculata*	Malvaceae
Mtandawara	*Markhamia lutea*	Bignoniaceae
Mlondondo	*Xeoderis stuhlmannii*	Fabaceae

Some species have not yet been identified. Mchenga in Nainokwe and Mtondoro in Nanjirinji had different local names, but were identified as the same species

where D_k is the DBH of each tree, and k is the stem number of each tree species.

Soil sampling and evaluation

Soil samples were collected from the center of each plot and defined as the equalized condition. At each sampling point, four soil cores were collected from 0–10, 45–55, 95–105 and 145–155 cm depth using a soil auger. Soil condition was evaluated in the field by Munsell soil color, finger soil texture, and soil pH (H_2O) measurement by a glass electrode pH meter (pH meter D-51, HORIBA, Kyoto, Japan) with a soil suspension 1 (soil): 2.5 (distilled water) ratio. Soil color was evaluated under sunlight according to the standard Munsell soil color chart, and soil texture was determined by finger test for moist soil samples with reference to the widely used USDA system [36].

Evaluation of surface appearance

The surface appearance of all living ABW trees in each plot over 10 cm DBH was evaluated according to the following criteria with reference to a previous report [37]. The lower part of the stem, from 0.3 up to 1.3 m, was divided into quarters virtually (Fig. 2), and each part was classified into one of four grades (0, 1, 2, 3) based on the ratio of clear areas with no visible defects, including cracks, holes, piths, etc. (Table 2). The grade of each living tree was obtained using the average of the four quarters.

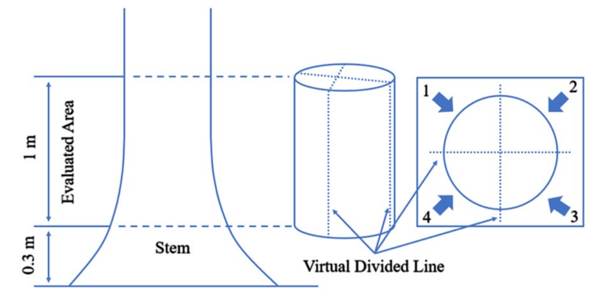

Fig. 2 Surface appearance evaluation. The numbers, 1, 2, 3 and 4, indicate the 4 evaluated surfaces on each stem. The average grade of each stem was calculated by all results from every surface

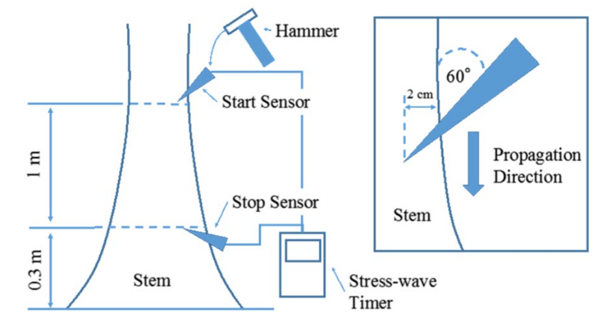

Fig. 3 An experimental set-up for measuring stress propagation time using FAKOPP as some species

Measurement of stress-wave velocity

The dynamic physical properties of living ABW trees were evaluated by measuring stress propagation time in trees with a microsecond timer, FAKOPP (FAKOPP Enterprise, Agfalva, Hungary). Stress propagation time is generally related to the dynamic physical properties of materials; in particular, the time in the L-direction of timbers can be converted to the dynamic Young's modulus using material density. Both start and stop sensors were set on a tree surface at a fixed distance (1 m) at a height of 0.3–1.3 m on the L direction of the tree. A stress wave was input by a single tap of a specific hammer (Fig. 3). Sensors were struck into the bark (2 cm deep) at a 60° angle to the surface (Fig. 3). Although the angle for this test is normally 45° [38], a larger angle was needed in this study due to the significant hardness of ABW.

Stress-wave velocity V_s (m/s) was approximately calculated by the following equation (Eq. 2):

$$V_s = \frac{L}{T} \quad (2)$$

where L is defined as the distance (1 m) between sensors, and T indicates the average stress propagation time of each tree [12 replications per tree: 3 times per quarter (Fig. 2)].

Data treatment and statistical analysis

Classification and ordination of tree vegetation data were performed based on total G of each species, and tree population of each plot. Tree population was calculated from the number of individuals with the biggest DBH of all stems in the case of multi-stemmed trees. Data items were statistically compared by Kruskal–Wallis test to analyze the relative effect of each factor. In addition, at 1% critical difference the Steel–Dwass test was used as a supplementary test. Every referenced plot was analyzed by the same method.

Results

Tree species composition

Figure 4 shows total G of all measured trees at each site calculated by Eq. 1. The total G values of the 3 sites were 15.07 m^2/ha in Kikole, 9.64 m^2/ha in Nainokwe, and 12.66 m^2/ha in Nanjirinji; Nainokwe was the lowest total G value was separated from other 2 sites. The same trend was found at reference plots (Kikole: 4.10 m^2/ha, Nainokwe: 2.66 m^2/ha, Nanjirinji: 3.72 m^2/ha). The average basal area of stands in Nainokwe was also smaller than the other sites, although the difference was not statistically significant at 1% level (Kikole–Nainokwe: $p=0.0260$, Nainokwe-Nanjirinji: $p=0.6045$, Kikole–Nanjirinji: $p=0.1271$). The tree species diversity was the lowest in Nainokwe where only three dominant species (Mpingo (ABW), Miombo and Msolo) have occupied more than 68% of total basal area. The G values of ABW at the 3 sites were 5.27 m^2/ha in Kikole, 4.19 m^2/in Nainokwe, and 5.20 m^2/ha in Nanjirinji. This was equal to ca.

Table 2 Grade list for wood evaluation

Grade	Clear part of surface (%)	Note (visual standard)
3	> 90	Extremely clear, no defects detected in visual inspection
2	60–90	Almost clear but some defects detected
1	30–60	Some serious defects on limited area of surface
0	0–30	Significant serious defects detected on wide area of surface

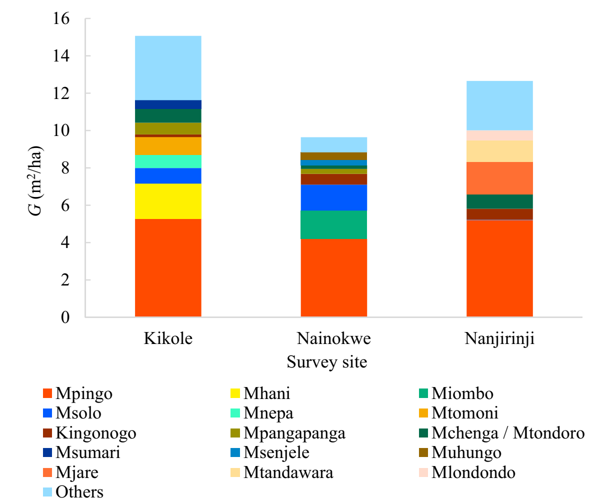

Fig. 4 Total *G* per hectare by species for three survey sites

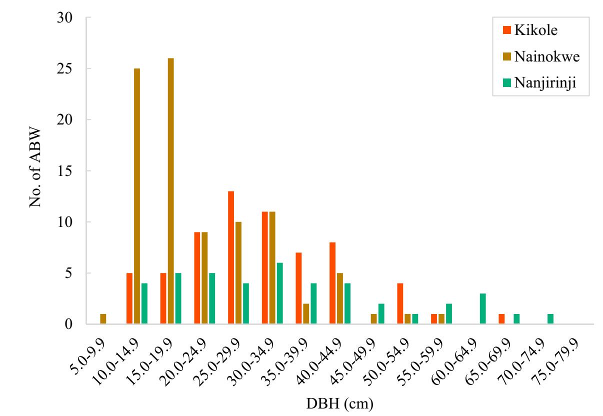

Fig. 5 Distribution of DBH at each site (ABW only)

35% of the total *G* value in Kikole, ca. 44% in Nainokwe, and ca. 41% in Nanjirinji (Fig. 4).

As shown in Table 3, the population density (number of individual trees/ha) of ABW was highest in Nainokwe (57.39 trees/ha), followed by Kikole (40.01 trees/ha), and Nanjiriji (31.94 trees/ha) (Table 3). In addition, the tree density of all species including ABW was also highest in Nainokwe (Table 3). Table 3 shows the growth form (DBH and tree height) of ABW in Nainokwe was also significantly smaller than at the other sites, whereas DBH of all species in Nainokwe was not statistically different from Nanjirinji ($p = 0.6201$) (Table 3).

Distribution of DBH and tree height of ABW trees are shown in Figs. 5 and 6, respectively. Nainokwe had an especially high number of small ABW trees (here we defined "small trees" as trees less than 20 cm DBH and 7 m height) (Fig. 5). The DBH distribution was quite different between Kikole and Nanjirinji, the number of mid-sized trees (20–40 cm DBH) in Kikole was also relatively larger than that of Nanjirinji, although tree height showed the same trend in both forests (Figs. 5, 6). Furthermore, in Kikole and Nainokwe there was a clear tendency of fewer trees with increased DBH, whereas Nanjirinji had a comparatively lower number of mid-sized trees (Fig. 5). Some big trees (DBH > 50 cm) were observed in all the sites, but there were fewer in Nainokwe (Fig. 5). Branch height was lowest in Nainokwe, although the difference was not statistically significant at 1% level ($p = 0.0474$) (Table 3).

Soil conditions

Tables 4 and 5 show soil data for the 3 sites whereby several soil types were observed, depending on the sampling location (depth and plot). The soil of the Kikole site was most sandy compared to the other 2 sites, with a range from clay loam (CL) to sandy loam (SL) (Tables 4, 5). On the other hand, most of soil samples in Nainokwe and Nanjirinji were evaluated as clay (C), with white crystal-like calcium carbonate (Tables 4, 5). There were no significant differences in soil pH (H_2O) between Nainokwe and Nanjirinji, but Kikole was significantly lower than the other sites (Table 4). Soils of yellowish to reddish colors (7.5YR–10.0YR in Munsell Color) were recorded for some plots in both Kikole and Nainokwe, whereas mostly dark-colored soil (blackish soil, less than 4.0 in color value) was observed in Nanjirinji. The same trend was also found in the reference plots (Tables 4, 5).

Table 3 Comparison of specified parameters among 3 sites

Forest	No./ha		DBH (cm)*		ABW Height (m)*	ABW Branch height (m)*
	ABW	Every tree	ABW	Every tree		
Kikole	40.91	159.09	34.87 ± 12.80^a	33.30 ± 13.28	10.54 ± 3.12^c	2.32 ± 1.25
Nainokwe	57.39	227.27	24.77 ± 11.91	21.11 ± 10.18^b	7.25 ± 2.58	1.21 ± 0.59^d
Nanjirinji	31.94	211.11	36.63 ± 17.16^a	23.62 ± 16.34^b	11.01 ± 2.86^c	1.52 ± 0.60^d

* Mean with the same letter are not significantly different (Steel–Dwass test, $p < 0.01$) following Kruskal–Wallis test

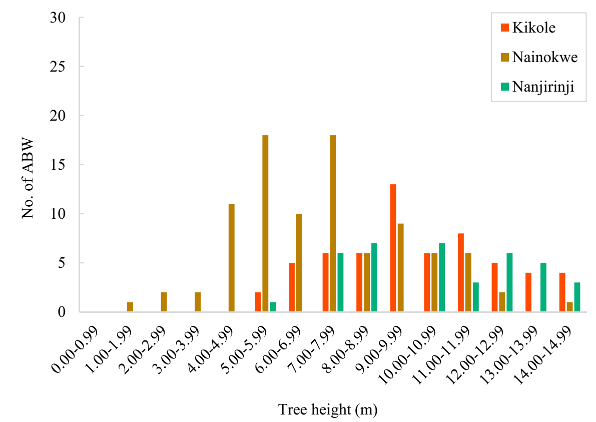

Fig. 6 Distribution of tree height at each site (ABW only)

Quality analysis of living trees

Evaluation values of the appearance of ABW trees were converted into an average grade: low: 0.00–0.99, middle: 1.00–1.99, or high: 2.00–3.00. Figure 7 shows the individual occurrence ratio of each grade in the Kikole, Nainokwe, and Nanjirinji sites. In Kikole and Nanjirinji, the majority of trees received a "Middle" grade, while Nanjirinji had a larger number of "High" appearance trees, over 30% (Fig. 7). On the other hand, most trees in Nainokwe were evaluated as "Low", and it had a much lower rate of "Middle" and "High" grade trees (Fig. 7).

As shown in Table 6, average stress-wave velocity (V_s) in Nanjirinji (2990 m/s) was higher than in the other sites (Kikole: 2808 m/s, Nainokwe: 2676 m/s); V_s in Nainokwe was the lowest value of all sites, and the difference

Table 4 Soil conditions in the three survey sites: soil texture, Munsell Color YR (mean ± SD), color value (mean ± SD) and pH (H_2O) (mean ± SD)

Survey site	*n*	Major soil texture	Munsell color YR*	Color value*	pH (H_2O)*
Sampling plot					
Kikole	44	SL–CL	8.2 ± 1.99[a]	4.7 ± 1.52	6.5 ± 0.98
Nainokwe	41	L–C	8.1 ± 2.08[a]	3.9 ± 0.72[b]	7.3 ± 1.05[c]
Nanjirinji	33	C	6.7 ± 1.46	3.1 ± 0.66[b]	7.5 ± 1.01[c]
Referenced plot**					
Kikole	8	SL–CL	7.8 ± 0.88	3.9 ± 0.83	6.5 ± 0.64
Nainokwe	8	LS–C	5.6 ± 1.16	4.1 ± 0.35	6.1 ± 0.84
Nanjirinji	6	C	6.7 ± 1.30	2.8 ± 0.41	7.2 ± 0.60

* Mean with the same letter are not significantly different (Steel–Dwass test; $p < 0.01$) following Kruskal–Wallis test

** Control plots were not statistically analyzed due to their limited replicates

Table 5 Soil texture data in all the sampling locations (*S* sand, *LS* loamy sand, *SL* sandy loam, *SCL* sandy clay loam, *SC* sandy clay, *L* loam, *LC* loamy clay, *CL* clay loam, *C* clay) including control plots (plot no. with a small letter, *)

Plot no.	Kikole				Plot no.	Nainokwe				Plot no.	Nanjirinji			
	10 cm	50 cm	100 cm	150 cm		10 cm	50 cm	100 cm	150 cm		10 cm	50 cm	100 cm	150 cm
1	C	C	CL	CL	1	LS[a]	SC	SC	SC	1	L	C	C	C
2	CL	SCL	SCL	S	2	LS	C[a]	C[a]	C[a]	2	LS	LS	SL	LS
3	SL	SL	SL	SCL	4	LC	C	C	C	4	C	C	C	
4	LS	LS	LS	LS	5	C	C	C	C	5	C	C	C	SC
5	SL	L	SCL	SL	6	C	C	C[c]	C	7	C	C	C	C
6	LS	SC	C	SCL	7	LC	C	C[c]	–	8	C	C[a]	C[a]	C[a]
7	S	SL	SL	LS	8	LC	C	SC[c]	–	9	SL	SC[a]	C[a]	C[a]
9	L	CL	C	C	9	C	C	C[a]	C	10	SCL	SC[a]	SC[a]	–
10	C	C	C	C	10	LC	C[a]	C[a]	C	11	LS	C	C	–
12	CL	CL	SL	LS	11	CL	C[b]	C[b]	–					
13	LS	SL	CL	SCL	12	CL	C	C	C					
8*	LS	L	SL	LS	3*	LS	CL	C	C	3*	LS	C	–	–
11*	CL	C	C	C	13*	LS	CL	CL	CL	6*	C	C	C	C

[a] $CaCO_3$

[b] Fe nodules

[c] $CaCO_3$ + Fe nodules. 10 cm, 50 cm, 100 cm and 150 cm: sampling depth from the ground level

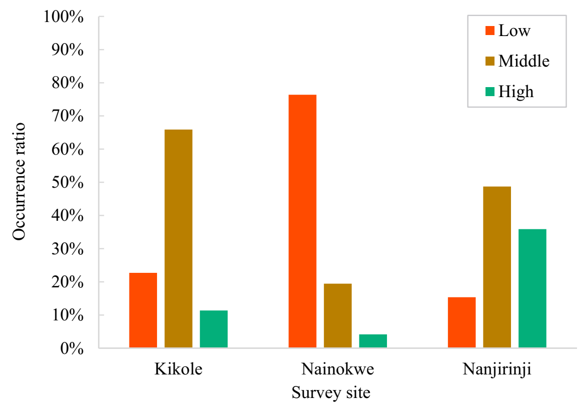

Fig. 7 Occurrence ratio of individuals evaluated at each site

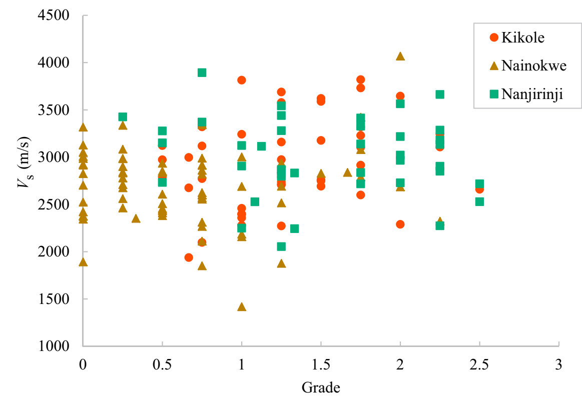

Fig. 9 Relationship between the evaluated appearance grade and stress-wave velocity (V_s) of ABW. Each correlation coefficient of the site was, respectively, showed as follows; Kikole: $r=0.2622$, Nainokwe: $r=0.0523$, Nanjirinji: $r=-0.1128$

Table 6 Average stress-wave velocity (V_s) of ABW trees in the survey sites

Survey site	V_s (m/s)*
Kikole	2808 ± 585^{ab}
Nainokwe	2676 ± 409^{a}
Nanjirinji	2990 ± 419^{b}

* Mean with the same letter are not significantly different (Steel–Dwass test; $p<0.01$) following Kruskal–Wallis test

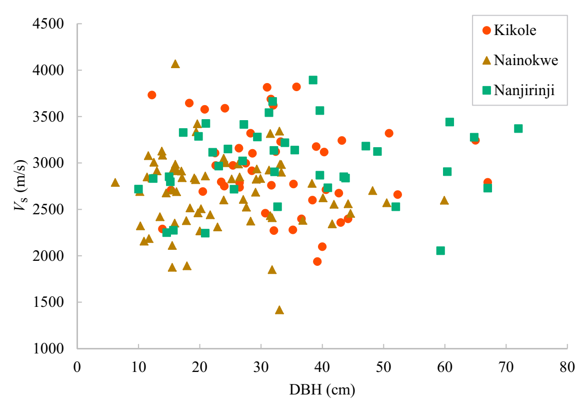

Fig. 8 Relationship between DBH and stress-wave velocity (V_s) of ABW. Each correlation coefficient of the site was, respectively, showed as follows; Kikole: $r=-0.1749$; Nainokwe: $r=-0.0999$; Nanjirinji: $r=0.1134$)

compared to the Nanjirinji site was significant at 1% level ($p<0.001$, Table 6) although there was no significant difference at 1% level among survey sites, Kikole and Nainokwe ($p=0.276$), Kikole and Nanjirinji ($p=0.241$).

When all V_s data of ABW trees was plotted against DBH (Fig. 8) and appearance evaluation value (Fig. 9), there was interestingly no clear tendency although poor correlation was found between V_s and appearance grade (V_s–DBH: $r=0.0637$, V_s–appearance grade: $r=0.2356$). Furthermore, there was no relationship in their parameters of each site (Figs. 8, 9) even though DBH, height and appearance of trees in Nainokwe was, respectively, inferior to those of the other 2 sites (Table 3). In addition, V_s against each appearance grade was further compared for only over middle grade (1.00–3.00). Poor correlation was showed between all V_s and appearance grades ($r=0.2512$), however, there was no significant difference at 1% level among survey sites (Kikole–Nainokwe: $p=0.1666$, Nainokwe-Nanjirinji: $p=0.9852$, Kikole–Nanjirinji: $p=0.0762$).

Discussion

In this study, we found that it is possible for ABW to survive under various environment conditions with high relative dominance. Different vegetation types were observed depending on the sample location (Fig. 4), and the vegetation surrounding ABW tree location significantly influenced their growth. Nainokwe site was significantly different from the 2 other sites in terms of tree species composition and growth form (Fig. 4, Table 3). Nainokwe site is mainly covered by wooded grassland, while open woodland covers larger areas of Kikole [33]. Although there has not yet been an official report, Nanjirinji site could also be categorized into mostly open woodland because of its statistical similarity to the parameters of Kikole site (Table 3, Figs. 4, 5 and 6).

Generally, there are many low trees with lower branch height in wooded grassland compared to open woodland [33] (Table 3, Fig. 6). In particular, some ABW trees in Nainokwe showed relatively small DBH in conjunction with tree height compared to those of other sites (Table 3,

Fig. 5). This forest had many juvenile ABW trees with small DBH and low height (Figs. 5, 6). Considering the diagnostic parameters listed in Tables 3 and 6, it seems that environmental impacts from forest parameters continuously influenced growth conditions.

On the other hand, the DBH of all trees in Kikole forest were significantly bigger than those of the other 2 sites, with an intensive number of mid-sized ABW trees, quite different from the Nanjirinji forest (Table 3, Fig. 5). This suggests that there might be a relationship between forest density and ABW regeneration. ABW has been known as a light-demanding species; thus, it might not regenerate under heavy closed vegetation [6, 39, 40]. In cases where the forest density is lower, ABW trees can also become multi-stemmed with smaller DBH and lower height. This is generally known as a typical physiological response. Trees in dense forests must compete for light, which places a premium on height growth, meaning that trees grow tall [32]. It was suggested that the significant difference of DBH distribution between Nainokwe and other sites was a result of the natural ABW habitat. Kikole forest apparently has the appropriate conditions under which ABW trees can coexist with other species because of both tree density and the number of individuals of each species (Table 3).

Furthermore, forest conditions including vegetation type generally depend on environmental factors such as topography, climate, and human activities. Tree growth can also be impacted by environmental factors such as topography, resource availability, and previous disturbance [31, 32]. The abundance, distribution, and diversity of vegetation tend to be strongly influenced by the qualities of the physical landscape, with plant species arising from both physical and chemical characteristics of the land [29]. Luoga et al. [41] reported that harvesting activity significantly affects the vegetation structure of woodlands, and the specific distribution of aged trees might be the result of clear-cutting of such trees [42]. Banda et al. [30] also reported that the gradient of land protection has been predicted to influence forest ecosystems in terms of growth form, regeneration, and species richness. As a result, some potential factors, including human activities such as fire and harvesting, have not yet been studied here. Further investigation should be conducted in terms of vegetation transition by human activities to clarify the specific distribution of ABW trees in natural forest.

Ilunga Muledi et al. [35] reported a variety of soil factors in a Miombo forest, and that vegetation was related to soil factors. In this study, we found a variety of soil types at the 3 sites: from sandy to clay, and with or without $CaCO_3$ and/or Fe nodules (Tables 4, 5). However, the results clearly suggest that ABW can grow in a wide variety of soil types regardless of their properties. In addition, in this study, dark-colored soils from CL to C soil texture observed in some plots in the Nanjirinji (Table 5), which might have better physical (better drainage and water-retention) and better chemical (more nutrients) properties.

In general, soil color depends on major inorganic components and the amount of organic matter, which determines the physical properties of the top soil. High clay content results in a high capacity for stocking organic matter, so that soil color darkens. Heavier clayey alkali-soil with high $CaCO_3$ content seems to affect root extension into deeper soil layers. In contrast, sandy soil (S), which was observed in Kikole, might have disadvantages for plant growth due to poor nutrients and low water holding capacity. The soils of Nainokwe were similar to those of Nanjirinji, although their vegetation obviously differed. We concluded that ABW trees could grow under a variety of soil types, and even where other plants cannot grow well. It has been suggested that rooting of ABW trees is not affected greatly by the soil condition due to their coexistence with mycorrhizal fungi, which fixes nitrogen and is commonly known to radiate out 30–50 m by root suckers [39, 43]. The survival of ABW was apparently the result of adaptation to a wide variety of soil conditions despite their less-competitive behavior in high-diversity dense forest.

Recently, studies of the relationship between tree growth and V_s have reported that velocity depends on planting density, which also influences tree-form properties such as bending, multi-stems, cracks, and decay. [37]. A positive relationship was observed between MOE and V_s of the living coniferous tree, Hinoki (*Chamaecyparis obtusa* Endle.) [38, 44, 45], and another positive relationship between wood hardness and V_s has been observed by using a stress wave timer in some tropical hardwoods (*Nectandra cuspidata*, *Mezilaurus itauba* and *Ocotea guianensis*) [46]. In addition, V_s, wood density and ultrasonic velocity which is another non-destructive measurement has also positively related to MOE of some planted hardwood trees (*Melia azedarch*, *Shorea* spp. and *Maesopsis eminii*) [47, 48]. Although wood density of the measured trees has not been evaluated in this study, the significant difference of wood density might result in the different V_s as shown in such current studies for other species. Evaluation of wood density thus should be needed for further discussing tree growth and wood quality. V_s is affected by defects such as cracks and pith including holes, because the stress-wave principally selects the shortest internal propagation route. Therefore, propagation time would be delayed by the existence of any serious defects between sensors. However, the physical quality of ABW was not significantly related to appearance conditions in this study, because there were only poor correlations between V_s and the appearance grades (Fig. 9), furthermore, V_s was also poorly correlated with appearance grades even in case of further analysis for only over middle grades.

African blackwood trees in Nainokwe site obviously had a worse appearance than those in the other 2 sites with the lower parameters in this study (Fig. 7, Table 3). This might have been due to the co-relationship between the environmental conditions and tree growth, although their growth rate have not completely evaluated yet. Trees on fertile, well-drained soils such as loam can grow rapidly, thus resulting in high density forest [33], but promoting fluting [31]. Fluting severity has been positively correlated with tree growth and branch height in Western Hemlock trees (*Tsuga heterophylla*) [49]. Furthermore, disturbances such as clear-cutting and mechanical stress can also induce more fluting [31]. Karlinasari et al. [48] also showed that negative correlations were found between wood quality traits (wood density, dynamic MOE and ultrasonic velocity) and tree volume at the planting sites of same aged trees. Since the stress-wave velocities (V_s) were not significantly different among survey sites with a variety of soil/landscape conditions (Table 6, Figs. 8 and 9), our findings suggest that the dynamic physical properties of ABW trees are not related to growth conditions in the natural forest, which is generally influenced by various external factors.

Conclusions

In this study, both the environmental conditions and physical properties of living ABW trees were investigated to figure out the appropriate conditions for growth and quality requirements as musical instruments. ABW can survive under various environmental conditions with intensive population. However, the trees living under inferior conditions in wooded grassland (Nainokwe) tended to have smaller DBH, lower height, and worse appearance. By contrast, the trees in open woodland, Kikole and Nanjirinji, showed better qualities in tree form and appearance. Especially, the trees tended to have larger DBH, higher height, and better appearance in Nanjirinji site where the soils with better properties were mostly observed. This suggested that soil condition could influence ABW growth. The difference of ABW growth form might be related to the light-demanding, and the influence of the struggle against other plant species. There was no significant difference in stress-wave velocities of living ABW trees from all 3 sites, even though we observed significant environmental effects on tree appearance. We therefore concluded that there were no significant effects of external factors on the real physical properties of trees as timber materials. Forest management should focus on producing high-yield trees with bigger DBH and higher branch height to achieve sustainability of ABW resources as an industrial material. Moreover, methods to increase the growth process while maintaining original specifications (i.e., dark-colored heartwood, high density) are needed in natural forest. We think that sustainable and healthy forest should be based on sustainable wood utilization.

As mentioned earlier, ABW is an endangered species, and thus plantations with proper management must be undertaken in near future, together with novel approaches for the effective utilization of currently unused parts of the trees. The results obtained in this study may contribute significantly to the sustainable production and utilization of this precious timber resource.

Abbreviations

ABW: African blackwood; NGO: Non-Government Organization; MCDI: Mpingo Conservation & Development Initiative; FSC: Forest Stewardship Council; PFM: Participatory Forestry Management System; REDD+: Reducing Emissions from Deforestation and forest Degradation, plus the sustainable management of forests, and the conservation and enhancement of forest carbon stocks; VLFRs: village land forest reserves; IUCN: International Union for Conservation of Nature; CITES: Convention on International Trade in Endangered Species of Wild Fauna and Flora; GPS: Global Positioning System; DBH: diameter of breast height; G: basal area of each tree; D_k: the DBH of each tree; k: the stem number of each tree; USDA: United States Department of Agriculture; V_s: stress-wave velocity; S: sand; LS: loamy sand; SL: sandy loam; SCL: sandy clay loam; SC: sandy clay; L: loam; LC: loamy clay; CL: clay loam; C: clay; MOE: modulus of elasticity.

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Authors' contributions

KN, MI and SO designed and mainly conducted the survey in this manuscript. KN analyzed and interpreted the data with MI, SO and TY. JT and MJ supported to implement survey and contributed to understand the general situation of local community forest. NML and VS also assisted in data collection including identification of local trees. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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