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Thinning intensity effects on diameter growth dynamics of African mahogany stands

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FOREST MANAGEMENT

ABSTRACT

Background: African mahogany (*Khaya* spp.) is a valuable timber species that has gained increasing attention in Brazil due to its silvicultural advantages over *Swietenia macrophylla*, particularly its superior growth performance and resistance to native pests. Thinning is a key silvicultural practice, yet optimal timing and intensity remain unclear for African mahogany, as most commercial timber has historically been sourced from native forests. This study evaluated the effects of different thinning intensities on diameter growth over four years in two African mahogany stands in Brazil (established in 2013 and 2014) with an initial density of 333 trees ha^{-1}.

Results: In 2020, a randomized complete block design with three replications was implemented, applying light (308 trees ha^{-1}), moderate (258 trees ha^{-1}), and heavy (206 trees ha^{-1}) thinning treatments. The statistical analysis was restructured using a factorial arrangement. Results indicated a significant effect of stand age ($p < 0.05$), whereas thinning intensity and the interaction between factors were not significant ($p > 0.05$). Complementary analyses using aligned rank transform (ANOVA -ART) were conducted to assess temporal variation within each stand, indicating increased diameter growth over time. Linear regressions showed DBH growth across treatments, and diameter distributions, modeled using the Weibull 3P function, shifted toward larger classes, particularly under moderate and heavy thinning.

Conclusions: Stand age was the main factor influencing diameter growth, while thinning intensity showed no significant overall effect under the factorial approach. However, temporal analyses suggest that density reduction contributes to shifts toward larger diameter classes, supporting thinning as a relevant management practice in African mahogany plantations.

Keywords: *forest management; Khaya grandifoliola; planted forest; silvicultural treatment; solid wood production.*

HIGHLIGHTS

Thinning was effective for increasing diameter increment
Diameters shifted to larger classes over time in the moderate and heavy treatments
Early density management promoted larger diameter
Moderate to heavy thinning yields long-term benefits for diameter growth.

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INTRODUCTION

Lumber produced by species of the *Khaya* genus, known as African mahogany, has gained a prominent position in the global wood market over the years. Traditionally sourced from native forests in the Ivory Coast and Ghana (ITTO, 2025), African mahogany wood is known for its high quality and durability (Faria et al., 2024), similar to big-leaf mahogany (*Swietenia macrophylla* King), which is native to tropical America. However, African mahogany can be produced in Brazilian plantations at a larger scale and lower cost, due to its resistance to the mahogany shoot borer (*Hypsipyla grandella* Zeller), a pest that causes significant timber and financial losses in big-leaf mahogany plantations (Reis et al., 2021). Additionally, while legal licenses are required for harvesting big-leaf mahogany in Brazil, African mahogany operations do not face such requirements (França et al., 2023).

Therefore, African mahogany plantations offer great potential for large-scale sustainable forestry in tropical regions under optimized silvicultural prescriptions. Increasing the supply of African mahogany wood in the market would meet a portion of the global demand for strong, resistant, and visually outstanding hardwood, including for big-leaf mahogany wood, due to the similarities between these products. Silvicultural prescriptions are applied to control certain environmental factors to achieve specific objectives with a stand overtime. Stand density can be controlled through silvicultural treatments such as crop tree release, pre-commercial thinning, and commercial thinning (Wagle et al., 2022, Moreau et al., 2022). Crop tree release aims to reduce competition around selected crop trees, whereas thinning involves stand-level interventions to modify density and structure by removing a portion of trees, thereby increasing growing space for the remaining individuals (Zou et al., 2023).

Commercial thinning, henceforward referred to as thinning, is a stand management treatment applied to reduce competition and increase growth rate of the remaining trees (Del Campo et al., 2022; Moreau et al., 2022). This removal of growing stock will result in an immediate reduction in total stand yield, as part of the stock is exported. In addition, there is a time lag before the remaining trees resume growth after competition is eliminated (Bradley, 1963). Detailed research is necessary to determine the optimal stand density for each site and species, according to the intended forest product, for optimized silviculture prescriptions.

Studies have investigated the effects of different thinning intensities on the growth and yield of the most common planted forest species in Brazil, such as: *Eucalyptus* spp. (Ferraz Filho et al., 2018; Keenan et al., 2021; Taylor et al., 2021), *Pinus* spp. (Grigoreva et al., 2022; Miranda et al., 2022) and *Tectonia grandis* (Souza et al., 2022). Although many entrepreneurs have chosen the *Khaya* genus for forest investments (Ribeiro et al., 2018; Reis et al., 2021), forest management regime and silviculture prescriptions for optimal plantations are recent in Brazil. Approximately 50,000 ha are currently covered by *Khaya* plantations, half of them concentrated in the Brazilian southeastern region in early stages of development (Ferraz Filho et al., 2021).

Thinning is a stand density management practice that significantly impacts stand structure, health, growth rate and yield. Hence, research on diameter growth as a function of thinning intensity for African mahogany trees, as performed in this study, is crucial to ensure optimized forest management for this species. To our knowledge, few studies have focused on *Khaya* plantation management (Mayrinck et al., 2018; Ribeiro et al., 2018). So far, the only research assessing the thinning effect on *Khaya* plantations is by Lafetá et al. (2022). However, they focused on simulating the effect of thinning intensity on net present value, like Ribeiro et al. (2018), and not on horizontal growth dynamics as we propose here. Therefore, the present study is the first to address the effect of thinning intensity on diameter distribution dynamics over time in *K. grandifoliola* stands in Brazil with the objectives of: (1) evaluate changes in tree diameters and growth rate under different thinning intensities (light, moderate, and heavy); (2) investigate the effect of thinning intensity over time at tree and stand level; and (3) model the diameter class distribution dynamics using the Weibull probability density function.

MATERIAL AND METHODS

Study area and Data collection

The study was conducted in two *K. grandifoliola* stands, covering a total area of 170 hectares. These stands were established in August 2013 and November 2014, with an initial density of 333 trees per hectare (6 m x 5 m) under an intensive management regime with drip irrigation system (~ 40 L per day). This forest is in Meta Forests Farm, owned by *Khaya* Woods, in Engenheiro Navarro, Minas Gerais, Brazil. The regional climate is classified as seasonal tropical (Aw) according to the Köppen classification (Alvares *et al*., 2013). Average summer and winter temperatures are 25°C and 22°C, respectively, and total annual average rainfall is 1.050 mm (Reboita et *al*., 2015) and the predominant soil class is Latosol (Santos *et al*., 2018).

The thinning experiment was installed in 2020, when 2013 and 2014 stands were 6.5 and 5.4 years old, respectively. The method applied was low thinning, aiming to eliminate suppressed, thin, leaning, broken, and forked trees, followed by intermediate trees, always observing an adequate geographical distribution of the remaining trees. The treatments applied were: (1) light thinning (308 remaining trees ha^{-1}); (2) moderate thinning (258 remaining trees ha^{-1}) and (3) heavy thinning (206 remaining trees ha^{-1}). Annual measurements were performed for four years following the thinning operation, starting in 2020.

To assess the effect of the thinning treatments, we established a complete randomized block design with three replications to evaluate the three thinning intensities treatments at both stands throughout the measurement period (Figure 1). Measuring plots encompassed 3 rows and 10 pits, totaling 30 pits per plot (900 m^2). We collected tree diameters at 1.30 m above ground level, referring to this measurement as diameter at breast height (DBH), using a metric tape.

Additionally, sample plots from a continuous forest inventory, performed regularly in the areas were used to characterize the pre-thinning aspects of the forest in 2019. The 2013 and 2014 stands had average DBH values of 21.0

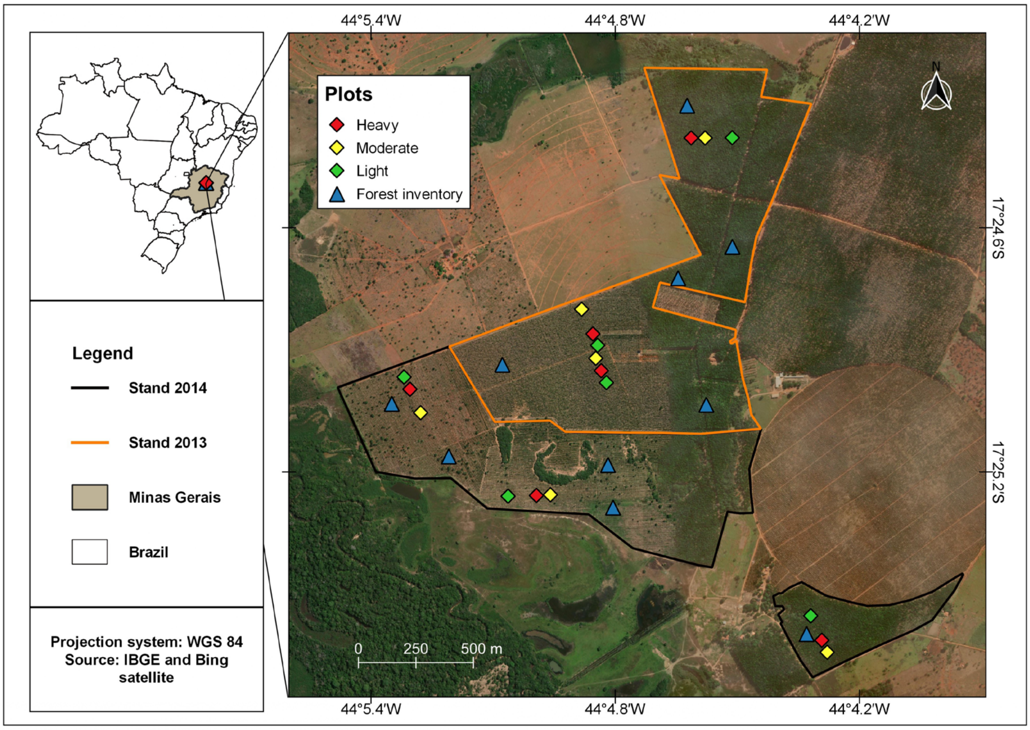

Figure 1: Thinning experiment plots and continuous forest inventory plots for two *Khaya grandifoliola* stands in Minas Gerais, Brazil.

± 2.4 and 19.2 ± 2.4 cm, respectively. Their basal areas were 11.6 ± 0.5 m^2 ha^{-1} and 9.5 ± 1.3 m^2 ha^{-1}, and their stand densities were 332 trees ha^{-1} and 322 trees ha^{-1}, respectively. These diameter production values represent a mean growth above 3.4 cm yea^{r-1}, which characterizes the study area as an average growth. Table 1 shows the average DBH and standard deviation for each thinning intensity over the years.

Data analysis

Mean annual increment in DBH (MAI in DBH) was calculated for each measurement year, stand, and treatment to assess the effect of thinning on growth rate. Statistical analyses were performed using R software (R Core Team, 2021). The experiment was established as a complete randomized block design with three blocks. For statistical analysis, the data were structured as a factorial arrangement, considering thinning intensity (3 levels) and stand age (2013 and 2014) as fixed factors, and blocks as experimental units. To ensure independence among observations and avoid pseudo replication, analyses were conducted using plot-level means.

A factorial analysis of variance (ANOVA) was performed to evaluate the effects of thinning intensity, stand age, and their interaction, adopting a significance level of 5% ($p < 0.05$). To assess temporal growth dynamics and account for deviations from normality, an aligned rank transform (ANOVA-ART) was performed separately for each stand, considering thinning intensity and measurement year as factors, using the ARTool package (Kay *et al.*, 2021). When significant effects were detected, Dunn's nonparametric multiple comparison test was applied ($p < 0.05$) with Bonferroni correction using the dunn.test package (Dinno, 2017).

Treatment effect was also assessed by comparing the DBH at each subsequent year with the DBH from the first

Table 1: Average of diameter at breast height (DBH), basal area (G) and standard deviation values for *Khaya grandifoliola* stands in Minas Gerais, Brazil.

Stand	Years after thinning	DBH (cm)			G (m^2 ha^{-1})		
		Light (308 N ha^{-1})	Moderate (258 N ha^{-1})	Heavy (206 N ha^{-1})	Light (308 N ha^{-1})	Moderate (258 N ha^{-1})	Heavy (206 N ha^{-1})
2013	1	22.4 ± 2.6	23.2 ± 2.3	22.5 ± 2.0	13.1 ± 0.3	10.5 ± 1	8.9 ± 1.4
	2	25.9 ± 3.2	27.6 ± 2.8	26.9 ± 2.8	17.1 ± 0.3	15.0 ± 0.7	12.7 ± 2.1
	3	27.4 ± 3.4	29.3 ± 3.3	28.9 ± 2.8	16.9 ± 3.5	16.9 ± 0.5	12.7 ± 1.3
	4	28.5 ± 3.7	30.5 ± 3.6	30.2 ± 3.0	18.2 ± 3.2	18.3 ± 0.4	13.9 ± 1.2
2014	1	20.1 ± 2.9	19.8 ± 1.8	19.8 ± 2.4	10.5 ± 0.3	6.9 ± 2.3	5.2 ± 2.1
	2	24.6 ± 3.5	25.0 ± 2.6	25.3 ± 3.0	13.7 ± 3.1	11.2 ± 3.5	8.5 ± 3.5
	3	26.0 ± 3.8	26.6 ± 2.9	27.1 ± 3.4	15.2 ± 3.3	12.7 ± 3.9	10.2 ± 3.6
	4	27.6 ± 4.1	27.8 ± 3.1	28.8 ± 3.6	16.7 ± 3.4	13.9 ± 4.2	11.5 ± 4.1

year after thinning. To do so, we fitted linear regressions for each measurement year, stand, and treatment, considering the DBH at each measurement year (from year 2 to 4) as the dependent variable and DBH immediately after thinning in the first measurement year as the independent variable, totaling 18 regression models. Initial model fitting attempts included an intercept variable to fit the models, however our initial results indicated only 2 yielded statistically significant intercept parameters ($p < 0.05$). Thus, we opted to standardize the fitted models by removing the intercept from all fitted models. After identifying the slope value of each linear regression equation for each treatment and stand, we plotted continuous variation curves to identify the DBH growth rates over time. A similar approach to assessing the effects of thinning on diameter growth was performed by Kim *et al*. (2016) and Peng *et al*. (2022).

Forest growth assessment resulting from thinning treatments was also assessed at both tree and stand levels. At tree level, changes were described in terms of DBH, while at stand level, changes were described based on basal area. Therefore, the impact of thinning on mean DBH and total basal area was evaluated using the light thinning treatment as the reference point. This was done by computing DBH and basal area values for the moderate and heavy thinning treatments relative to those of the light thinning treatment across all measured ages. This approach allowed for the assessment of thinning effects as the stands aged, expressed as percentage changes in DBH and basal area over time.

Finally, the effects of the thinning treatments on stand structure were assessed with a three-parameter Weibull probability density function (1). This function was fitted to describe the diameter distribution of the stands under different thinning intensities over time. The location parameter (a) was defined as the minimum diameter at breast height (DBH), while the scale (b) and shape (c) parameters were estimated by maximum likelihood using the fitdist function from the R environment (Delignette-Muller and Dutang, 2015). The goodness-of-fit was assessed using the Kolmogorov-Smirnov Test (K-S test) (1) with a critical value of $\alpha = 0.05$, as described in Peng *et al*. (2022).

$$f\left(x\right) = \left(\frac{c}{b}\right) * \left(\frac{(x-a)}{b}\right)^{c-1} * \exp\left[-\left(\frac{(x-a)}{b}\right)^{c}\right] \qquad (1)$$

where x is the diameter at breast height (DBH), a is the location parameter, b is the scale parameter and c is the shape parameter.

RESULTS

Effects of thinning on mean annual DBH increment

The factorial ANOVA indicated that thinning intensity did not significantly affect MAI in DBH ($p = 0.380$). In contrast, stand age had a significant effect on growth ($p= 0.012$), indicating differences between the evaluated stands. The interaction between thinning intensity and stand age was not significant ($p = 0.665$), suggesting that the response to thinning was consistent across both stands. In addition, no significant effect of blocks was observed ($p = 0.476$).

Although thinning intensity was not statistically significant, a tendency of increased MAI in DBH was observed under higher thinning intensities across measurement periods. The ART analysis, performed separately for each stand, revealed significant temporal variation in MAI in DBH, indicating that growth changed over time following thinning. In the 2013 stand, differences among thinning intensities varied across measurement years, whereas in the 2014 stand, growth patterns were more homogeneous over time (Figure 2). There was no significant interaction between mean annual increment in DBH (MAI in DBH) values over the years ($p > 0.05$) for either the 2013 or 2014 stands ($p = 0.4245$ and $p = 0.5917$, respectively). For the stand 2013, different thinning intensities resulted in significant differences for MAI in DBH ($p < 0.05$). However, no significant differences between treatments were detected for 2014 ($p = 0.7465$). For both stands, the effect of measurement year (time after thinning) was significant for MAI in DBH values ($p < 0.05$). Dunn's test was performed for mean comparison of MAI in DBH values (Figure 2). The 2014 stand presented a similar trend compared to 2013 stand, with the highest MAI in DBH on the heavy and moderate treatments, followed by the light thinning intensity.

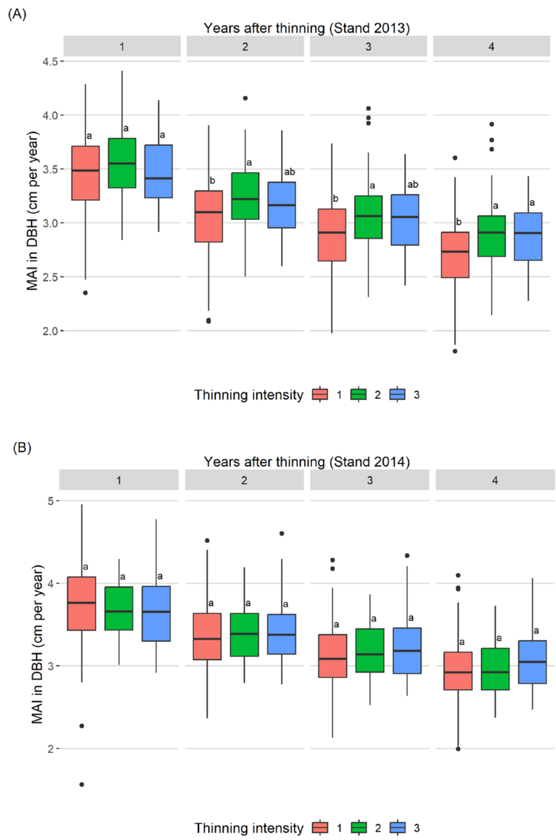

Figure 2: Mean annual increment in diameter (MAI in DBH, cm $year^{-1}$) of *Khaya grandifoliola* for the stands 2013 (A) and 2014 (B) in Minas Gerais, Brazil, measured over four years after thinning. Letters above the boxplots indicate significant differences among treatments according to Dunn's multiple comparison test ($p < 0.05$).

Effects of thinning on stand structure and DBH growth

Figure 3 shows the diameter at breast height (DBH) shortly after thinning (measurement 1 on the x-axis) versus DBH at measurements 2, 3, and 4 (on the y-axis) for each treatment in the 2013 and 2014 stands. The growth rate for each treatment, stand, and year following thinning is evidenced by the slope of each linear regression. For both stands, it is noticeable that the light thinning intensity resulted in more similar diameter values across different measurement years, indicating slower growth over. In contrast, moderate and heavy thinning intensities caused more noticeable growth, evidenced by the fact that diameters are more distinguishable at the third and fourth measurements. The slope values on the light treatment assumed more similar values over the years than the slope values on the moderate and heavy treatments.

The slope values displayed on Figure 3 for both stands and treatments increased over time (Figure 4). The heavy thinning treatment consistently presented the highest slope values for all measuring years, followed by moderate and light thinning intensities. For example, the highest slopes for the 2013 and 2014 stands were 1.34 and 1.46 cm, respectively, at the heavy thinning treatment at the fourth measurement. It means that four years after thinning, the heavy treatment yielded 1.34 and 1.46 larger DBH values compared to the first measurement at the 2013 and 2014 stands, respectively. The moderate and heavy treatments yielded similar growth performances in both stands, particularly in stand 2013, compared to the light treatment, which presented the lowest slopes for all measured years.

The effect of thinning on individual tree size tends to be positive after the remaining stock resumes growth after competition elimination. However, a stand's total stock takes more time to re-establish, since the number of individuals being accounted for in terms of basal area and total volume is reduced. Figure 5 presents DBH and basal growth variation, in percentage, for the moderate and heavy thinning treatments in relation to the light thinning treatment. Four years after thinning, we found that the thinning treatments had an overall positive impact on tree production (DBH) and negative impact on stand production (basal area). A noticeable positive effect

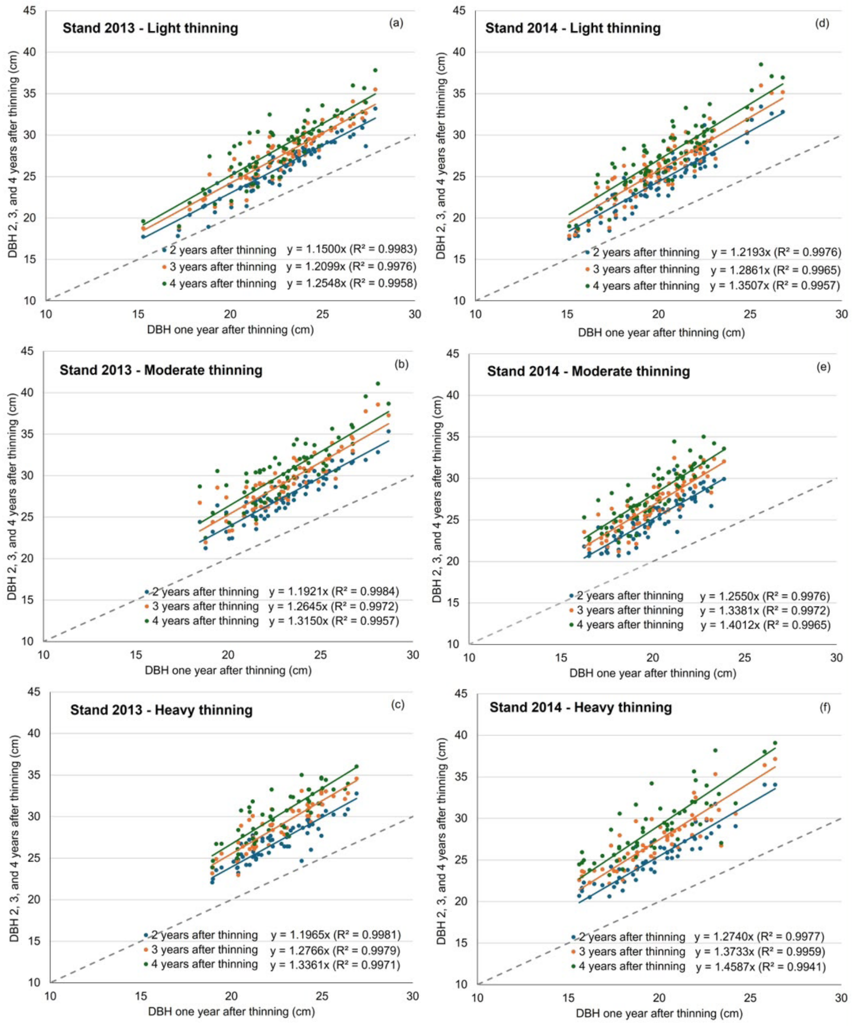

Figure 3: Diameter at thinning against diameter after thinning on measurements 2, 3, and 4 for the light (a), moderate (b) and heavy (c) treatments for 2013 and light (d), moderate (e) and heavy (f) treatments for 2014 stands of *Khaya grandifoliola* in Minas Gerais, Brazil. The dashed line is 45° angle, which indicates that the trees are not growing over time.

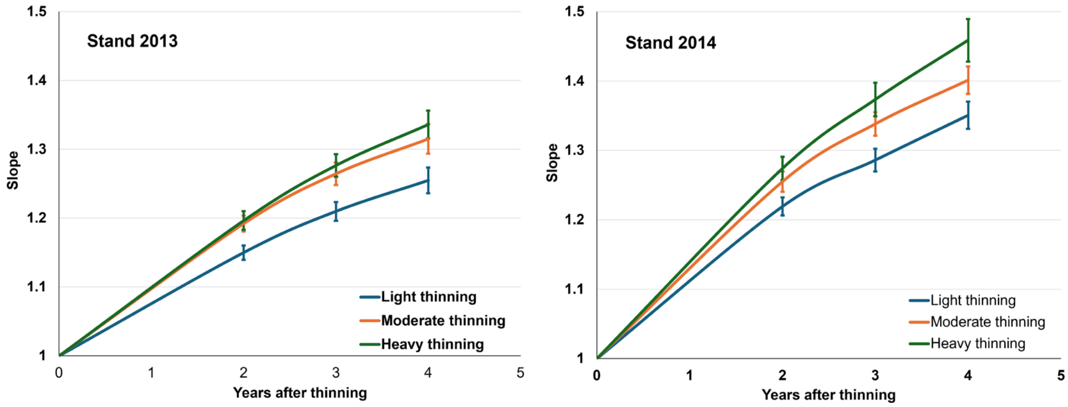

Figure 4: Slope of diameter growth over time for *Khaya grandifoliola* stands for different thinning intensities (where vertical bars represent the 95% confidence interval), in Minas Gerais, Brazil.

of thinning on DBH growth can be observed after the second year following the operation. Basal area dropped immediately after the thinning procedure, and it tends to increase over the years following the thinning operation, which is more pronounced at stand 2014 than on stand 2013. On the 2013 stand, the basal area of the moderate thinning treatment was re-established to light thinning levels 3 years after the thinning operation. For the heavy intensity on both stands, and for the moderate intensity on the 2014 stand, four years after thinning, basal area is still less than 80% and 90% of the light thinning levels, respectively.

In the 2014 stand, the heavy thinning treatment presented the same trends seen in stand 2013, with a mean DBH around 5% higher and a basal area about 25% lower than the light thinning treatment 4 years after thinning (Figure 5). The relative stand production of the moderate and heavy thinning regimes increased as the stands aged. For example, the basal area at the heavy thinning treatment increased from 60% of the light thinning basal area one year after thinning to 75% four years after thinning. Similarly, the moderate treatment increased its basal area from 82% of the light thinning basal area to 91%.

The Weibull distribution provided a good fit to the data for both the 2013 and 2014 stands across all treatments and measurement years (Table 2). The location parameter was lowest under light thinning intensity in both stands and increased over time. Similar trend was observed for the scale and measurement periods in both stands. Mean diameter at breast height (DBH) followed the same pattern as the Weibull parameters in both stands, with lower values under light thinning, followed by moderate and heavy thinning intensities, and increasing over time.

The Weibull probability density function curve fitted for each treatment and stands over time is shown on Figure 6. For all treatments, the curves became broader over the years, meaning that stand homogeneity tends to decrease over time, with this effect more pronounced for the 2014 stand. The difference between the treatments is more evident two years after thinning, with pronounced differences at the fourth measurement for both stands (at age of 10.5 and 9.4 for the stands 2013 and 2014, respectively).

DISCUSSION

African mahogany cultivation is in a relatively early stage in Brazil, making research on optimizing silvicultural treatments for solid wood production essential. Currently, Brazilian silviculture for African mahogany typically applies low initial planting densities, commonly 6 m x 6 m spacing

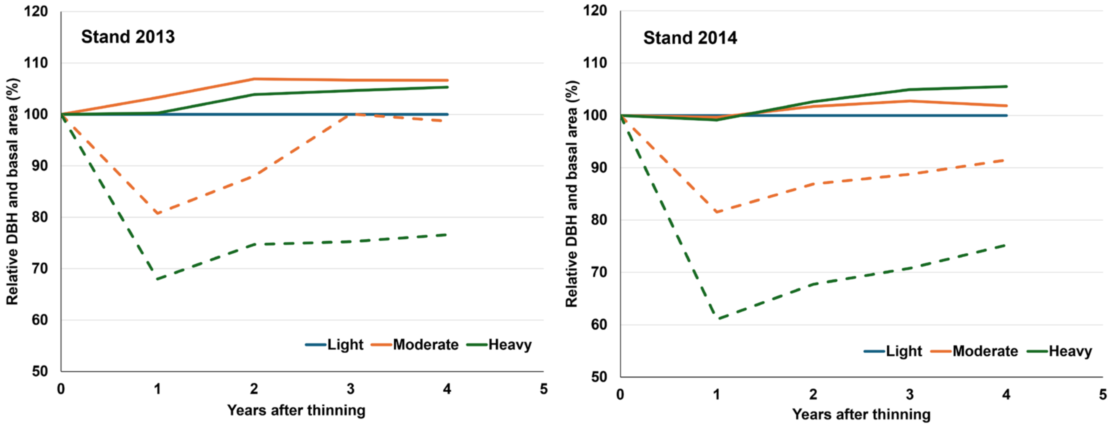

Figure 5: Response percentage to thinning in mean diameter at breast height (DBH – solid line) and basal area (G – dashed line) under different thinning treatments in 2013 and 2014 *Khaya grandifoliola* stands, in Minas Gerais, Brazil (relative increment under light thinning intensity = 100%).

Table 2: Weibull function parameters and DBH of two *Khaya grandifoliola* stands (2013, 2014) in Minas Gerais, Brazil, for different thinning intensities over time. Calculated (Dn) and tabled KS (D 0.05) value with 95% of confidence.

Stand	Thinning intensity	Years after thinning	Location	Scale	Shape	Dn	D 0.05
2013	Light	1	15.3	23.6	9.8	0.15	0.48
		2	17.7	27.3	9.3	0.12	0.43
		3	18.8	28.9	9.1	0.13	0.43
		4	19.0	30.1	8.6	0.13	0.41
		Average	17.7	27.5	9.2	0.13	0.44
	Moderate	1	18.5	24.2	10.8	0.15	0.39
		2	21.3	28.9	10.3	0.22	0.45
		3	22.0	30.8	8.7	0.22	0.41
		4	22.5	32.0	8.3	0.19	0.41
		Average	21.0	29.0	9.5	0.19	0.42
	Heavy	1	18.9	23.4	12.1	0.10	0.43
		2	22.1	28.0	12.0	0.17	0.52
		3	23.0	30.1	11.7	0.14	0.48
		4	23.9	31.5	11.7	0.13	0.45
		Average	22.0	28.3	11.9	0.14	0.47
2014	Light	1	8.4	21.2	8.1	0.17	0.41
		2	17.5	26.2	7.6	0.14	0.43
		3	17.9	27.7	7.4	0.17	0.41
		4	18.7	29.3	7.3	0.17	0.39
		Average	15.6	26.1	7.6	0.16	0.41
	Moderate	1	16.3	20.9	12.0	0.08	0.45
		2	20.7	26.3	10.6	0.07	0.38
		3	21.2	28.1	10.1	0.15	0.48
		4	22.3	29.5	9.6	0.15	0.48
		Average	20.1	26.2	10.6	0.11	0.45
	Heavy	1	15.6	21.0	8.2	0.15	0.48
		2	20.5	26.8	7.9	0.17	0.45
		3	22.2	28.9	7.6	0.19	0.45
		4	23.2	30.8	7.6	0.13	0.43
		Average	20.4	26.9	7.8	0.16	0.46

(Ferraz Filho *et al*., 2021). Our study aimed to address the existing knowledge gap in African mahogany forest management by focusing on understanding the effect of thinning on growth rate, diameter distribution, and stand yield in low-density stands. There are some limitations in our study, including the reduced number of sampling plots, single-site assessment, and the absence of an unthinned control treatment and prior measurements in the same sample plots. Despite these limitations, this study provides a valuable opportunity to enhance our understanding of stand density management in African mahogany stands, given the scarcity of literature on this topic.

Important aspects when performing thinning operations, such as timing and intensity, depend on species and growing conditions. Guidelines are often based on growth or harvesting models developed for specific species and regions (Rajeev *et al*., 2023), which may not be directly applicable to African mahogany under tropical conditions. Assessing thinning impacts requires long-term experiments, ideally covering a full rotation period (Pretzsch, 2020). There are still no well-defined rotation ages for African mahogany in Brazil, although practical recommendations range from 15 to 20 years (Ribeiro *et al*., 2018), extending up to 30 years. In this study, stands were monitored for approximately 11 years, with detailed assessments conducted over four years following thinning. Although longer-term monitoring is still required, this study provides one of the earliest evaluations of post-thinning responses in African mahogany stands.

MAI in DBH was affected by thinning over the years, despite the initial low planting density. However, the absence of statistically significant differences among thinning treatments in the 2014 stand contrasts with the more variable response observed in the 2013 stand. This discrepancy can be associated with differences in stand developmental stage at the time of thinning. The 2014 stand was thinned earlier (5.4 years), when competition among trees was likely still low, reducing the immediate impact of thinning on growth. In contrast, the 2013 stand, thinned at 6.5 years, may have already experienced some levels of competition, making it more responsive to density reduction. In addition to age-related effects, potential differences in site conditions, including soil properties and microenvironmental variability, may also have contributed to the observed responses.

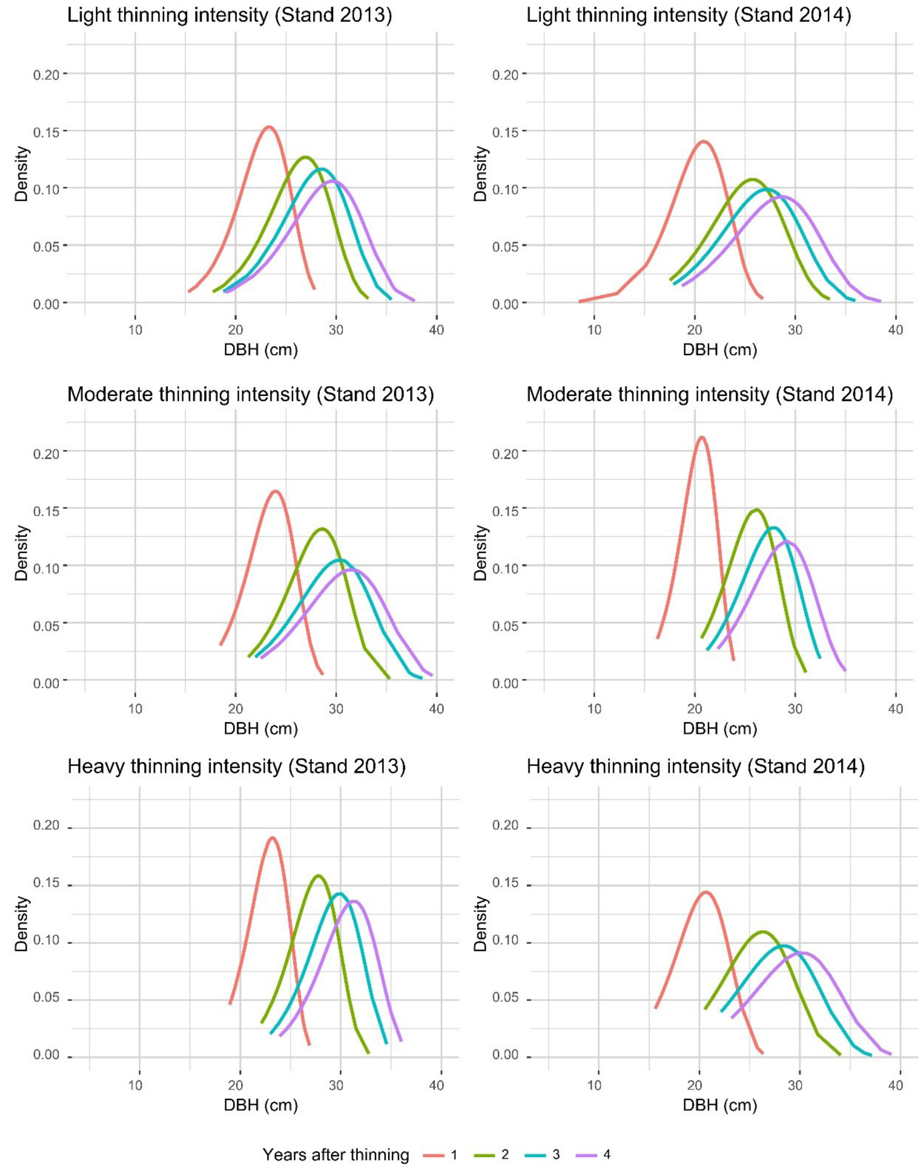

Figure 6: Diameter distributions fitted by Weibull 3P probability density function for two *Khaya grandifoliola* stands (2013 and 2014) in Minas Gerais, Brazil, for the light, moderate and heavy thinning treatments over time.

Even under similar management, small variations in water and nutrient availability can influence the magnitude of thinning effects. These factors likely contributed to the lack of statistical significance observed in the 2014 stand ($p = 0.7465$), despite showing similar growth trends to the 2013 stand. The wide initial planting spacing (30 m^2 per tree), combined with early thinning, further explains the limited differentiation among treatments, particularly in the younger stand. Under such conditions, resource availability is less restrictive, and thinning effects may not translate into significant differences in diameter growth in the short term. Similar results were reported by Peng *et al*. (2022), who found non-significant differences among thinning treatments in *Swietenia macrophylla*, although moderate and heavy thinning promoted similar individual tree growth.

MAI in DBH and the slope values on the linear regressions at each measurement were generally higher under heavy thinning, followed by moderate and light thinning. The increasing slope over time indicates that stands continued responding positively to thinning up to four years after application. This suggests that competition has not yet intensified to levels that would reduce growth rates. However, a decline in growth is expected as stands mature and competition increases, potentially requiring additional thinning interventions, as reported in previous studies (Kim *et al*., 2016; Pretzsch, 2020; Peng *et al*., 2022).

The Weibull probability density function was chosen to represent the diameter distribution of the stands because of its flexibility and its proven ability to represent forest stands (Bailey and Dell, 1973; Peng *et al*., 2022;

Alkan, 2025). The location parameter (a) describes where the diameter distribution starts in the assessed forest, which in this study was assumed to be the smallest observed diameter. The heavy treatment presented a higher minimal diameter than the moderate intensity, followed by the light intensity at both stands. Although the forest did not have enough time to respond to the thinning treatments in the first measurement, the location parameter was already clearer on the medium and heavy thinning treatments than in the light treatment. This was expected, since a low thinning was performed, removing the smallest trees from the stand and automatically shifting the location parameter's value in those treatments.

Additionally, because the location parameter represents the smallest tree in the forest and because trees with the lowest DBH typically have their crowns in a lower layer in the canopy, these trees tend to grow at a lower rate compared to other trees in the stand due to reduced access to light. This means the location parameter tends to change less than the other parameters and is less affected by changes in thinning intensity in the stand. At both stands and all treatments, the location parameter's value increased over the years, showing that the diameter of the trees grew during the assessment period, including the small, suppressed trees. Similar results were found by Mayrinck *et al*. (2018), who fitted the Weibull probability density function for *Khaya* stands, reporting values for the location parameter rising from 4.4 to 16 at 4 to 14 years old, respectively.

The scale parameter (b) is related to the size of the most frequent diameters. For both stands, the scale parameter increased over the years, which indicates DBH growth over time, corroborating with Das *et al*. (2018), studying *Swietenia macrophylla* stands, who also found increasing values for the scale parameter as the stand ages. At both stands, the moderate and heavy thinning intensities showed similar values, followed by the light intensity (Figure 6 and Table 2). Comparable studies have also illustrated the stand density effect on scale parameters for *Khaya* stands in Brazil, with values ranging from 10.4 at stands with 400 trees ha-1 to 14.2 at stands with 100 or less trees ha-1 (Mayrinck *et al*., 2018).

The shape parameter (c) describes the form of the diameter distribution curve. When c ≤ 1, the distribution assumes a reverse-J shape, whereas values approaching 3.6 indicate a distribution closer to normal. Values greater than 3.6 indicate increasing negative skewness, reflecting a higher proportion of larger-diameter trees (Bailey and Dell, 1973; Bončina *et al*., 2022). In this study, the high values of the shape parameter indicate strongly negatively skewed distributions, suggesting that thinning promoted trees in larger diameter classes. This pattern is consistent with the expected effects of thinning, which reduces competition and reallocates resources to the remaining trees, enhancing diameter growth. The observed increase in distribution width over time suggests a reduction in stand homogeneity, indicating that thinning also influences structural variability.

Differences among thinning intensities reinforce that the level of intervention affects not only central tendency but also the overall distribution of tree sizes. Similar trends have been reported by Ganbaatar *et al*. (2021) in *Pinus sylvestris* stands, where moderate and high thinning intensities promoted greater diameter development compared to lower intensities. Although individual Weibull parameters provide useful insights into stand structure, the diameter distribution should be interpreted as a whole. In this context, thinning intensity influences not only the central tendency of diameters but also stand homogeneity, which is an important attribute for forest management.

The intensity of the treatments affected homogeneity over time. Observing the diameter probability density function for the 2013 stand on the fourth measurement, for example, the heavy treatment yielded a more homogeneous stand than the light treatment. This can be explained by the fact that the heavy treatment provided more trees with the opportunity to grow in an open space within the canopy, so less competitive and uniform environment for more trees than light treatment, which provided fewer trees with an open space in the canopy (Peng *et al*., 2022). A homogeneous stand creates better evenly distributed conditions over the stand for more trees, which contributes towards more optimized growing conditions, optimizing yield (Oliveira *et al*., 2024).

Another benefit of a homogeneous tree distribution in the stand is related to the reduction of tree growth stress, which can cause processing defects during logging and lumbering (Rozas *et al*., 2023). In accordance, Pretzsch (2020) found that silvicultural interventions promote a stratified canopy for *Picea abies*, resulting in superior growth which highlights the importance of creating canopy gaps for intermediate trees in the stand to increment their growth. The author emphasized that the impact of reducing tree density in forest stands and the best thinning methods are old and still controversial topics that continually require new studies assessing individual cases.

Analyzing DBH growth at the 2013 stand four years after thinning, the heavy and moderate thinning treatments tended to present similar DBH values (Figure 5), 6% larger in average than the DBHs at the light thinning treatment. In terms of basal area, the moderate thinning intensity compensated for the elimination of trees by growing the remaining stock 3 years after thinning, while the heavy treatment presented 70% of the basal area found in the light thinning (Figure 5). Therefore, it took 3 years following thinning for the moderate thinning intensity treatment to establish a basal area like light intensity treatment, the baseline scenario. The heavy treatment at both stands did not restore its basal area to the light thinning levels during the assessment period.

Moderate and heavy thinning treatments promoted greater individual tree growth but resulted in lower total stand production compared to light thinning, reflecting the classical trade-off between individual tree size and stand yield (Bradley, 1963; Rajeev *et al*., 2023, Liu *et al*., 2025). Different thinning regimes create a tradeoff between single tree (DBH) and total stand growth (basal area) (Ferraz Filho *et al*., 2018; Šilinskas *et al*., 2024). For example, Zhang *et al*. (2009) in their study on the impact of thinning on tree growth, lumber yield, and lumber quality in *Abies* balsamea, reported that heavy thinning is recommended if the goal is to produce sizeable sawlogs in the shortest time, whereas moderate thinning is preferable if the intention is to minimize the negative effects on lumber quality while retaining modest tree growth and lumber yield.

The main goal of the forest of this study is to produce high-value lumber products, such as described in França *et al*. (2023) and Ribeiro *et al*. (2023). Thus, the decrease in total stand production caused by thinning procedures in stands destined for lumber products can be compensated for by the value of the increased merchantable volume of these stands. McGavin *et al*. (2021) highlight how important large-diameter trees are for veneer production. Their study material in Australian plantations shows that veneer recovery from *Khaya senegalensis* timber ranged from 42% to 55%, depending on the method (spindle-less lathe technology or traditional sawing techniques) but in all cases, yield was diameter-related. Beyond yield, thinning can also affect wood properties like elasticity, density, and stiffness (Gendvilas *et al*., 2021; Resquin *et al*., 2024).

Except for the MAI in DBH for stand 2014, all variables accessed in this study indicated that the heavy and moderate thinning treatments yielded noticeable effects in tree and stand growth dynamics. The differences between the heavy and moderate treatments depended on the age at which thinning was applied. When thinning was performed at 6.5 years of age (stand 2013), the differences between the heavy and moderate treatments were small or nonexistent. However, when the thinning operation was performed at a younger age (5.4 years, stand 2014), the heavy treatment was able to achieve higher diameter growth rates than the moderate and light treatments.

Overall, the results indicate that thinning effects on African mahogany growth are influenced by stand age, timing of intervention, and temporal dynamics. While thinning did not show a significant effect in the overall factorial analysis, temporal variation and structural changes suggest that its effects are dynamic and may become more pronounced over time. These findings reinforce the importance of long-term monitoring to fully understand the role of thinning in tropical plantation management.

CONCLUSION

Thinning plays a key role in shaping the horizontal structure and growth dynamics of African mahogany stands. Moderate to heavy thinning intensities promoted the development of larger and more uniformtrees, making them suitable for higher-value timber products. However, these treatments may reduce stand-level yield, highlighting the need to balance individual tree growth and total production. Given the limitations of the dataset, these findings should be interpreted with caution. Thus, thinning decisions should be guided by site-specific management objectives and complemented by continued monitoring and further studies to better define optimal thinning regimes for different production goals, particularly through long-term experiments covering the full rotation.

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AUTHORSHIP CONTRIBUTION

Project Idea: AR; MMA; ACFF
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Writing: AR; RM; CSJS; LRG; AJAR; MMA; ACFF
Validation: AR; MMA
Review: AR; RM; XMO; CSJS; LRG; AJAR; MMA; ACFF

DATA AVAILABILITY

The datasets supporting the conclusions are included in the article.

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