

Post-harvest silviculture reduces cutting cycles: the case of *Tachigali glauca*, an Amazonian commercial species

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Abstract

Reduced-impact logging (RIL) has improved operational practices in tropical forests, yet increasing evidence shows that it alone is insufficient to restore commercial timber stocks within realistic cutting cycles. Post-harvest silvicultural interventions in logging gaps have therefore been proposed to accelerate tree growth and shorten rotation lengths. We evaluated the long-term effects of post-harvest silviculture on growth, survival, biomass accumulation, and stem volume of *Tachigali glauca*, a fast-growing and light-demanding Amazonian timber species. We monitored trees established under three treatments, control (RIL only), tending of natural regeneration, and enrichment planting, across 17 years in logging gaps. Periodic annual increments in diameter, aboveground biomass, and volume were quantified, and growth projections were used to estimate time to reach the minimum cutting diameter of 50 cm. Mortality rates were low within all treatments. In contrast, growth responses differed markedly: enrichment planting resulted in the highest diameter, biomass, and volume increments, followed by tending and control treatments. Diameter growth was primarily driven by silvicultural treatment rather than crown exposure class, indicating that structural management effects outweighed fine-scale light variation. Diameter class distributions revealed faster structural advance under enrichment planting, with a greater proportion of individuals reaching larger size classes by 2023. Growth projections indicated that enrichment planting reduced the estimated time to reach 50 cm DBH to approximately 54 years, compared to 93 years under tending and 175 years under control conditions. Our results demonstrate that post-harvest silviculture (particularly enrichment planting) substantially accelerates growth trajectories and reduces rotation length.

1. INTRODUCTION

Sustainable timber production from selectively logged tropical forests remains one of the central challenges of forest management in the Amazon. Although reduced-impact logging (RIL) has substantially decreased immediate ecological damage compared to conventional practices, growing evidence indicates that RIL alone is insufficient to ensure the recovery of commercial timber stocks within realistic cutting cycles. Long-term empirical studies and modeling approaches consistently show that natural regeneration and residual tree growth under RIL frequently fail to replenish harvested volumes within 25–35-year rotations, leading to progressive depletion of commercial species and extended recovery times that are incompatible with polycyclic management objectives (Sist and Ferreira 2007; Valle et al. 2007; de Avila et al. 2017; Sist et al. 2021).

This limitation has been reinforced by simulation-based and empirical analyses demonstrating that, regardless of logging intensity or cutting cycle length, selectively logged forests tend to have declining timber stocks when post-harvest interventions are absent. For several tropical regions, including the Amazon and Southeast Asia, recovery of original stand structure and species composition often requires many decades, far exceeding conventional management cycles (Shima et al. 2018; Pioniot et al. 2019; Sist et al. 2021). Consequently, the long-term sustainability of timber production increasingly depends on

the integration of active post-harvest silvicultural practices designed to accelerate growth, recruitment, and structural recovery of commercial species.

Post-harvest silvicultural treatments applied in logging gaps, such as liberation thinning or tending and enrichment planting, have emerged as effective tools to overcome the limitations of natural regeneration in managed tropical forests. Experimental evidence from the Amazon and other tropical regions shows that these interventions enhance light availability, reduce competition from lianas and non-commercial species, and promote faster diameter growth, biomass accumulation, and volume recovery of target trees (Peña-Claros et al. 2008; Doucet et al. 2009; Schwartz et al. 2013, 2017a; Neves et al. 2019). Enrichment planting has been shown to substantially increase stem density and growth rates of commercial species in canopy gaps, improving the predictability of timber recovery and shortening the time required to reach harvestable sizes (Gourlet-Fleury et al. 2013; Schwartz et al. 2017b; Sist et al. 2021).

Light-demanding and pioneer commercial species are especially responsive to these post-harvest interventions. Among them, *Tachigali glauca* stands out as a fast-growing and heliophilous tree species widely distributed in the eastern and central Amazon. Its functional traits (rapid juvenile growth, strong responsiveness to canopy opening, and high commercial value) make it a suitable model species for evaluating the effectiveness of silvicultural treatments in logging gaps (Foster 1977; Schwartz et al. 2017a). Previous studies in the eastern Amazon have indicated that *T. glauca* exhibits enhanced growth and favorable cost–benefit ratios when subjected to tending or enrichment planting, highlighting its potential role in strategies aimed to restore commercial timber stocks (Schwartz et al. 2016; Neves et al. 2019).

Despite these evidences, most Sustainable Forest Management Plans (SFMPs) in the Brazilian Amazon still rely solely on RIL without systematic investments in post-harvest silviculture. As a result, management prescriptions often underestimate the time required for commercial species to reach the minimum cutting diameter (MCD), generating overly optimistic expectations regarding future yields (Roopsind et al. 2017; Ferreira et al. 2020). Bridging this gap requires long-term empirical assessments that explicitly link silvicultural treatments to growth trajectories, demographic structure, and projected time to commercial size. Thereby it needs to provide robust information for yield regulation, rotation length definition, and public policy design.

In this context, the present study evaluates the medium- to long-term effects of post-harvest silvicultural treatments applied in logging gaps on the growth, survival, biomass accumulation, and volume production of *Tachigali glauca* in logging gaps of a managed forest in the eastern Amazon. By integrating 17 years of field monitoring with growth projection analyses, we quantify how control conditions, tending of natural regeneration, and enrichment planting influence individual performance and population structure, as well as the time required to reach the commercial diameter threshold of 50 cm. We hypothesize that active silvicultural interventions, particularly enrichment planting, substantially accelerate growth trajectories and reduce rotation length compared to reliance on natural regeneration

alone, enhancing the feasibility of sustainable polycyclic forest management in Amazonian production forests.

2. MATERIAL AND METHODS

2.1. Study Area

The study was conducted in a managed tropical forest located in the Jari Valley, municipality of Almeirim, Pará State, eastern Brazilian Amazon (approximately 1°09' S, 52°38' W). The region is characterized by a humid tropical climate or Af (Köppen classification), with mean annual precipitation around 2,200 mm and a short dry season between August and November. Mean annual temperature is 26°C. The dominant vegetation type is dense ombrophilous forest or terra firme forest, growing predominantly on dystrophic yellow Latosols, which are widespread across the landscape.

The experiment is part of a long-term research initiative coordinated by Embrapa Eastern Amazon in cooperation with Jari Florestal S.A., focusing on post-harvest silviculture in logging gaps within reduced-impact logging (RIL) systems. Jari Florestal manages 545,500 ha of tropical forest under a polycyclic silvicultural system, with all harvesting operations conducted under RIL guidelines. Timber extraction in the study area occurred in 2004 and 2006, resulting in the formation of canopy logging gaps of varying sizes and shapes.

The study area has been the focus of continuous forest monitoring and silvicultural experimentation for nearly two decades, providing a robust empirical basis for evaluating medium- and long-term responses of commercial tree species to post-harvest interventions. Detailed descriptions of forest structure, species composition, and pre-logging conditions of the management unit are available in previous studies carried out in the same area (Schwartz et al. 2013; de Souza et al. 2014; Neves et al. 2019).

2.2. Experimental Design and Silvicultural Treatments

A total of 181 individuals of *Tachigali glauca* (Fabaceae) were monitored over time, including both naturally regenerated and planted trees. These individuals were unevenly distributed among the silvicultural treatments, with 35 individuals assigned to the control treatment, 17 subjected to tending practices and 129 established through enrichment planting. Silvicultural interventions were implemented repeatedly throughout the monitoring period (2006 up to 2023) in treatments.

In control treatment, logging gaps were left under standard reduced-impact logging conditions without any post-harvest silvicultural intervention, allowing natural forest regeneration. As expected, logging gaps under this treatment contained a mixture of naturally regenerating tree species, among which *T. glauca* was one of the focal commercial species monitored in this study.

The tending treatment focused on assisting natural regeneration through liberation practices designed to reduce competition from neighboring vegetation, including lianas and tree species. Although multiple

tree species occurred within these gaps, management actions and subsequent analyses in the present study were restricted to naturally regenerated commercial individuals, like *T. glauca*.

The planting treatment was established in one-year-old logging gaps following complete removal of logging residues for energy production by the forestry company. Enrichment planting involved *T. glauca* seedlings planted at a spacing of 2.5×2.5 m without fertilization. In addition to *T. glauca*, a limited number of other native commercial tree species were also planted within the same gaps as part of the broader silvicultural program; however, the present study focuses exclusively on the performance of *T. glauca* individuals across treatments.

Logging gaps provided the environment in which silvicultural treatments were applied with trees constituted the primary sampling and analytical units. This individual-based approach allowed the assessment of survival, growth, diameter structure, biomass accumulation, and projected growth trajectories while accounting for the spatial and environmental heterogeneity inherent to gap formation in managed tropical forests.

2.3. Measurements and Data Collection

Forest inventories were conducted repeatedly between 2006 and 2023, encompassing the years 2006, 2007, 2008, 2009, 2010, 2012, 2017, and 2023. All individuals of *T. glauca* occurring within the logging gaps assigned to each silvicultural treatment were individually tagged and permanently marked to allow long-term monitoring. The same individuals were remeasured across successive inventories whenever possible.

During each census, diameter at breast height (DBH) was measured at 1.30 m above ground using a diameter tape. Tree status (alive or dead) was recorded at each measurement, allowing the construction of individual growth trajectories and the estimation of mortality rates over time. Only individuals with complete measurement records and confirmed survival throughout the growth interval considered in each analysis were included in growth-related assessments. This criterion ensured that periodic annual increments reflected true growth responses rather than artifacts associated with missing data or delayed recruitment.

Crown exposure was classified using an adapted Crown Exposure Class (CEC) system following Clark and Clark (1992) and Dawkins and Field (1978). Under the gap conditions of this study, crown exposure was assessed using four ordinal classes (1.5, 2.0, 2.5, and 3.0), representing a gradient of increasing light availability. Classes 1.5, 2.0, and 2.5 correspond to crowns receiving lateral light only, with no direct vertical light exposure, and were distinguished according to the relative intensity of lateral illumination: low (CEC = 1.5), intermediate (CEC = 2.0), and high lateral exposure (CEC = 2.5). Class 3.0 represents crowns receiving partial direct vertical light, with approximately 10–90% of the vertical crown projection exposed to direct radiation. This approach avoided circularity between growth and exposure while allowing crown position to be evaluated as an explanatory variable.

Logging gap size was quantified by measuring the longest and shortest diameters of each gap and calculating gap area using the ellipse formula. Gap size was recorded to characterize the physical environment in which individuals developed and to provide contextual information regarding light availability and structural openness. Even though logging gaps constituted the spatial framework for silvicultural interventions, individual trees were treated as the primary sampling units in all analyses.

Annual mortality rates were estimated using the exponential model of Sheil et al. (1995), which is well suited to forest monitoring data with irregular census intervals. The model assumes a constant mortality probability within each interval and allows mortality rates to be standardized on an annual basis, enabling comparisons among treatments and census periods of unequal duration. Annual mortality (m , % yr⁻¹) was calculated as:

$m = 1 - \left(\frac{N_t}{N_0} \right)^{\frac{1}{t}}$, where N_0 and N_t represent the number of surviving individuals at the start and end of each census interval, respectively, and t is the interval length in years. Cumulative survival was computed as the product of survival probabilities across successive intervals.

To estimate aboveground biomass (AGB) and stem volume, all DBH measurements were converted using species-specific allometric models widely applied in Amazonian forest management. Aboveground biomass (kg) was estimated using the DBH-based allometric model of Nogueira et al. (2008), calibrated for central and western Amazonian forests: $AGB = \exp(-1.716 + 2.413 \cdot \ln(DBH))$. Stem volume (m³) for each individual was estimated using the equation of Silva et al. (1985), originally developed for dense ombrophilous forests in the Tapajós region:

$$V = \exp(-7.62812 + 2.1809 \cdot \ln(DBH)).$$

2.4. Growth Analyses

2.4.1. Periodic annual increment (PAI)

Tree growth was quantified using periodic annual increment (PAI) in diameter at breast height (DBH), aboveground biomass, and stem volume. Growth analyses were restricted to individuals that survived and had complete DBH, biomass, and volume measurements at both the beginning (2010) and end (2023) of the interval ($n = 117$). PAIs for DBH, biomass, and volume were calculated for each individual as: $PAI = \frac{X_{2023} - X_{2010}}{13}$, where X represents DBH, aboveground biomass, or stem volume, and 13 corresponds to the length of the interval in years. PAI values are expressed as cm yr⁻¹ for DBH, kg yr⁻¹ for aboveground biomass, and m³ yr⁻¹ for stem volume.

2.4.2. Diameter Class Structure

Diameter structure was analyzed to describe the size distribution of *T. glauca* individuals under different silvicultural treatments at the end of the monitoring period. DBH measurements from the 2023 inventory were grouped into fixed diameter classes of 5 cm width. This class interval was selected to balance resolution and interpretability while allowing clear visualization of structural differences among treatments. Analyses were solely descriptive and aimed to illustrate how silvicultural interventions influenced population-level size structure over time. No statistical tests were applied to diameter class

distributions. The number of individuals per diameter class was summarized separately for each treatment and presented graphically to facilitate comparisons of structural development and progression into larger size classes.

2.4.3. Projection of Time to Commercial Diameter (50 cm DBH)

2.4.3.1. Empirical basis

Projections of diameter growth were based on the observed periodic annual increment in DBH (PAIDBH) calculated for the 2010–2023 interval. This period was selected as the empirical basis for projections because it represents a post-establishment phase in which seedlings and saplings had already overcome initial transplant or recruitment effects and exhibited more stable growth trajectories across treatments. Under this interval, it was avoided bias associated with early post-logging variability and ensured that projections were grounded in observed medium-term growth performance. Initial DBH values used in the projections corresponded to individual measurements recorded in 2010, which served as the reference year for all simulated growth trajectories.

2.4.3.2. Hybrid growth model

Projected diameter growth followed a hybrid modeling approach that combined empirical linear growth with a reduction in increment at larger diameters. Specifically, DBH was assumed to increase linearly according to the observed mean PAI for each treatment until individuals reached 35 cm DBH. This threshold was adopted because many long-lived hardwood species exhibit linear diameter growth during juvenile and subcanopy stages, followed by a progressive decline in increment after canopy accession. Besides this threshold, annual diameter increment was progressively reduced to account for ontogenetic growth deceleration commonly observed in tropical hardwood species. Such growth deceleration has been widely attributed to factors including increased hydraulic limitation, higher maintenance respiration costs, and shifts in carbon allocation as trees approach reproductive maturity. This simplified representation of growth dynamics was adopted to balance biological realism, avoiding the use of asymptotic growth functions that are difficult to parameterize with limited data at large diameters, while still capturing the expected slowdown in diameter increment as trees approach maturity.

2.4.3.3. Bootstrap procedure

Uncertainty in growth projections was quantified using a non-parametric bootstrap procedure. For each silvicultural treatment, individual PAI_{DBH} values were resampled with replacement 1,000 times to generate distributions of mean annual increment. These resampled increments were used to simulate alternative growth trajectories, propagating variability in observed growth rates through the projection process. From the resulting ensemble of simulated trajectories, point estimates and 95% confidence intervals (2.5th–97.5th percentiles) were derived for projected DBH over time and for the estimated time required to reach the commercial diameter threshold.

2.4.3.4. Truncation at commercial diameter

Growth projections were truncated when simulated DBH reached the minimum cutting diameter of 50 cm. The primary outcome of the projection analysis was therefore the estimated time required for individuals under each silvicultural treatment to attain commercial size, rather than long-term asymptotic growth behavior. This truncation emphasizes the applied relevance of the analysis for forest management, directly linking observed growth responses under different silvicultural interventions to expected rotation length and harvest planning in managed tropical forests.

2.5. Statistical modeling

Statistical analyses were conducted to evaluate the effects of silvicultural treatments on growth, biomass accumulation, and stem volume of *T. glauca*. Treatment effects on diameter, biomass, and volume increments were assessed using linear mixed-effects models (LMMs), with silvicultural treatment as a fixed effect and logging gap as a random intercept to account for the hierarchical structure of the data and non-independence of trees within gaps.

The analysis of diameter increment in relation to crown exposure class (CEC) assessed in 2010 was performed using a two-way ANOVA including treatment, CEC, and their interaction. A logarithmic transformation was applied to biomass increment data and a Box–Cox transformation to volume increment data to meet assumptions of normality and homoscedasticity; diameter increment data required no transformation. Model assumptions were checked using Shapiro–Wilk tests for normality and Levene’s tests for homogeneity of variances.

Mortality was analyzed using a binomial generalized linear model (GLM). When significant effects were detected, pairwise comparisons among treatments were performed using estimated marginal means with Tukey adjustment. Variance associated with logging gaps was consistently low (approximately 10–12% of total variance for diameter and biomass increments, and negligible for volume increment). Furthermore, non-parametric Kruskal–Wallis tests were applied to biomass and volume increments to confirm the robustness of results in the presence of deviations from normality.

2.6. Software and Reproducibility

All data processing, statistical analyses, and figure generation were conducted in R (version 4.3.1 or later). Core statistical analyses were performed using base R functions (stats package) and the car package (for Levene’s tests). Linear mixed-effects models were fitted using the lme4 package, and post-hoc comparisons of estimated marginal means were carried out with the emmeans package (Tukey adjustment). Compact letter displays for significance were generated using the multcompView package. Graphical outputs were produced using ggplot2 and tidyr. Bootstrap procedures for growth projections were implemented using the boot package, and Box–Cox transformations were performed with the MASS package. Non-parametric tests were conducted with base R (kruskal.test). Statistical significance was evaluated at $\alpha = 0.05$. The analytical workflow was fully scripted, ensuring transparency and reproducibility of all analyses and results.

3. RESULTS

Annual mortality probability of *Tachigali glauca* did not differ significantly among silvicultural treatments over the monitoring period. Binomial generalized linear models indicated no significant effect of treatment on mortality probability ($p > 0.05$), although slight differences in mortality trajectories were observed over time. Overall mortality rates remained low across treatments (less than 1.2%), indicating that neither tending nor enrichment planting increased mortality relative to standard reduced-impact logging conditions (Fig. 1).

Periodic annual diameter increment (PAI_{DBH}) differed significantly among silvicultural treatments (linear mixed-effects model with gap as random effect; approximate $F_{2,20.9} = 21.8$, $p < 0.001$; Fig. 2). Trees established under enrichment planting showed the highest growth rates (estimated marginal mean $\pm$ SE: 1.07 ± 0.08 cm year⁻¹), significantly exceeding those in the tending (0.59 ± 0.13 cm year⁻¹) and control treatments (0.31 ± 0.10 cm year⁻¹). Pairwise comparisons (Tukey-adjusted) confirmed that enrichment planting differed significantly from both control ($p < 0.0001$) and tending ($p = 0.0047$), whereas tending did not differ significantly from control ($p = 0.119$). Variance associated with logging gaps was low (10.3% of total variance), indicating minimal influence of gap-level clustering on treatment inferences.

When diameter growth was evaluated in relation to crown exposure class assessed at the beginning of the growth interval (2010), silvicultural treatment remained the dominant factor controlling growth (ANOVA, $p < 0.001$), whereas crown exposure class had no significant effect ($p = 0.86$), and no interaction between treatment and crown exposure class was detected ($p = 0.49$; Fig. 3). Although mean diameter increment tended to increase with crown exposure within treatments, these differences were not statistically significant, both in the overall model and in analyses conducted separately for each treatment.

Annual biomass increment differed significantly among silvicultural treatments (ANOVA on log-transformed data, $F_{2,114} = 27.99$, $p < 0.001$). Enrichment planting presented the highest biomass accumulation, with a mean PAI_{AGB} of 13.5 ± 1.0 kg year⁻¹, followed by the tending treatment (8.3 ± 3.9 kg year⁻¹), while the control treatment showed the lowest values (2.9 ± 1.2 kg year⁻¹). Linear mixed-effects models with logging gap as random effect yielded consistent results ($p < 0.001$), with variance associated with gaps accounting for approximately 12% of total variance. Pairwise comparisons using Tukey's HSD test indicated that all treatments differed significantly from each other ($p < 0.05$). These results were corroborated by a non-parametric Kruskal–Wallis test ($\chi^2 = 30.34$, $p < 0.001$), confirming the robustness of treatment effects on biomass accumulation (Fig. 4).

Annual periodic increment in stem volume differed significantly among silvicultural treatments (ANOVA on Box–Cox transformed data, $F_{2,114} = 27.68$, $p < 0.001$; Fig. 5). Trees established under enrichment planting exhibited the highest volume increment (mean $PAI_V = 0.018 \pm 0.002$ m³ year⁻¹), followed by the tending treatment (0.010 ± 0.003 m³ year⁻¹), whereas the control treatment displayed the lowest annual volume increment (0.003 ± 0.001 m³ year⁻¹). Pairwise comparisons using Tukey's HSD test indicated that

all treatments differed significantly from each other ($p < 0.05$), with enrichment planting outperforming both control and tending, and tending exceeding control conditions. These differences were robust to departures from normality, as confirmed by a non-parametric Kruskal–Wallis test ($\chi^2 = 30.21$, $p < 0.001$). Linear mixed-effects models confirmed these patterns ($p < 0.001$), with negligible variance associated with logging gaps (singular fit).

The diameter class distribution in 2023 differed markedly among silvicultural treatments (Fig. 6). Under enrichment planting, individuals were predominantly concentrated in the intermediate and larger diameter classes, with most trees occurring between 10–15 cm and 15–20 cm DBH, and a substantial number already reaching the 20–25 cm and 25–30 cm classes, indicating rapid structural development over the monitoring period. In contrast, individuals in the control treatment were largely restricted to the smallest diameter classes, being mainly concentrated in the 0–5 cm and 5–10 cm classes, with only a few individuals progressing beyond 10–15 cm, reflecting slower growth and limited upward movement along the diameter distribution. The tending treatment showed an intermediate pattern, with individuals distributed primarily across the 5–10 cm and 10–15 cm classes and a small representation in the 15–20 cm and larger classes, but substantially fewer individuals in the upper diameter classes than observed under enrichment planting.

Projected diameter growth trajectories of *T. glauca* differed markedly among silvicultural treatments when extrapolated from periodic annual diameter increments observed between 2010 and 2023. In 2010, individuals included in the analysis exhibited small and relatively similar mean diameters among treatments, ranging from approximately 3 to 5 cm, indicating early developmental stages at the reference year used for the projections.

Clear contrasts were observed in the estimated time required for trees to reach a diameter of 50 cm. Individuals under enrichment planting reached this threshold in the shortest time, with an average of 54 years from the 2010 reference point. Trees subjected to tending exhibited intermediate growth trajectories, reaching 50 cm after 93 years, whereas individuals in the control treatment required substantially longer periods, with an estimated time of 175 years to attain the same diameter (Fig. 7).

4. DISCUSSION

4.1. Silvicultural interventions as primary drivers of growth responses

Silvicultural interventions dominated post-harvest growth responses in *Tachigali glauca*, with enrichment planting yielding the highest periodic annual increments (PAI) in diameter ($\approx 1.07 \text{ cm yr}^{-1}$), aboveground biomass ($\approx 0.35 \text{ Mg yr}^{-1} \text{ ind}^{-1}$), and volume ($\approx 0.003 \text{ m}^3 \text{ yr}^{-1} \text{ ind}^{-1}$), followed by tending ($\approx 0.65 \text{ cm yr}^{-1}$, $\approx 0.20 \text{ Mg yr}^{-1} \text{ ind}^{-1}$, $\approx 0.002 \text{ m}^3 \text{ yr}^{-1} \text{ ind}^{-1}$) and controls ($\approx 0.38 \text{ cm yr}^{-1}$, $\approx 0.12 \text{ Mg yr}^{-1} \text{ ind}^{-1}$, $\approx 0.001 \text{ m}^3 \text{ yr}^{-1} \text{ ind}^{-1}$). This hierarchy underscores how active management, through gap preparation, residual and

competitor removal, and seedling establishment, overrides natural regeneration limitations in RIL systems (Lopes et al. 2008; Schwartz et al. 2012, 2013; Neves et al. 2019).

Long-term evidence from Amazonian managed forests indicates that RIL alone is insufficient to restore commercial timber stocks within 25–35-year cutting cycles, largely due to slow residual growth and limited recruitment of commercial species (Sist and Ferreira 2007; Valle et al. 2007; Roopsind et al. 2017; de Avila et al. 2017; Sist et al. 2021). In contrast, post-harvest silvicultural interventions, particularly enrichment planting, mitigate these constraints by increasing stem densities and light availability in logging gaps, sustaining medium-term diameter increments of approximately $0.8\text{--}1.2\text{ cm yr}^{-1}$ over years, consistent with our observations (Doucet et al. 2009; Schwartz et al. 2013; Neves et al. 2019). Similar growth enhancements have been reported in Central African forests under post-logging thinning, where diameter increments of $0.5\text{--}0.8\text{ cm yr}^{-1}$ scale with disturbance intensity and competitive release (Gourlet-Fleury et al. 2013), reinforcing the need of active silvicultural management to accelerate growth trajectories and shorten rotation lengths in tropical production forests.

Tending provides moderate growth enhancements by liberating natural regeneration from lianas and competing vegetation, but its effectiveness depends on the availability of pre-existing commercial stocks, which are often limited in pioneer-dominated logging gaps (Villegas et al. 2009; David et al. 2019). Liana cutting and thinning further increase diameter increments and have been shown to potentially shorten cutting cycles by alleviating competitive constraints on residual trees (Slätis et al. 2025; Dionisio et al. 2025). Across growth metrics, enrichment planting consistently produces substantially higher biomass and volume accumulation than passive or low-intensity interventions, reflecting more efficient carbon allocation under high light conditions in managed gaps, particularly in forests developed on nutrient-poor Latosols (Feldpausch et al. 2012).

Natural regeneration frequently fails to provide sufficient commercial yields after selective logging, as post-harvest stands often show low densities of target species, making active intervention necessary to sustain future production (Rheenen et al. 2004; Park et al. 2005; Schwartz et al. 2017a, b). In this context, enrichment planting functions as a form of assisted densification, accelerating the development of population structure toward future harvestable classes while reconciling timber production with conservation objectives (Schwartz and Lopes 2015; Schwartz et al. 2016). Evidence from tropical forests further indicates that interventions enhancing early growth reduce uncertainty in timber volume recovery and contribute to more predictable productivity in managed systems (Rozendaal et al. 2010; Roopsind et al. 2017).

4.2. Limited role of crown exposure once silvicultural structure is established

Even though crown exposure class (CEC) is widely used as a proxy for light availability and competitive status in tropical forests, it did not emerge as a significant predictor of growth. While CEC captures short-term variation in crown illumination, post-harvest interventions (such as enrichment planting, tending, liana cutting, and thinning) act as persistent structural modifiers of the growth environment,

reshaping light regimes, neighborhood competition, and belowground interactions over extended periods (Peña-Claros et al. 2008; Schwartz et al. 2013; DeArmond et al. 2023).

Differences between enrichment planting and tending further illustrate this structural control. In planting treatments, individuals are established under defined spacing within high illumination microsites. This reduces early crowding, stabilize neighborhood competition, and ensure sustained access to resources, whereas growth responses under tending depend on the heterogeneous spatial distribution and prior growth history of naturally regenerated individuals embedded in pioneer-dominated matrices (Schwartz et al. 2013; Gourlet-Fleury et al. 2013).

From a functional perspective, these results align with classical gap dynamics theory, which predicts that light is a dominant driver for establishment and early recruitment but becomes progressively less limiting as individuals attain structurally favorable canopy positions (Swaine and Whitmore 1988; Clark and Clark 1992). Empirical syntheses further demonstrate saturation of light effects in tropical forests, beyond which growth responses are driven by competition, tree size, and management history rather than fine-scale variation in canopy openness (Montgomery and Chazdon 2001; Fredericksen and Putz 2003). By demonstrating that treatment-induced structural controls (including spacing and sustained competitor control) override crown-scale light heterogeneity, our study advances current understanding of why CEC may lose explanatory power in managed gaps. This is not due to light relevance, but because active silviculture has already standardized light and competitive environments at levels sufficient to sustain rapid growth. This reinforces a central management implication widely supported in the literature, namely that designing and maintaining favorable structural conditions is more effective for enhancing growth and shortening rotation lengths than reliance on naturally variable light environments alone (Putz et al. 2001; Gourlet-Fleury et al. 2013; DeArmond et al. 2023).

4.3. Consistency among diameter, biomass, and volume increments

Across treatments, growth responses of *T. glauca* were remarkably consistent among diameter, aboveground biomass, and stem volume increments, indicating that silvicultural effects reflected coherent ecological processes rather than metric-specific artifacts. Enrichment planting consistently produced the highest periodic annual increments for all three variables, followed by tending and control treatments, confirming that accelerated diameter growth translated proportionally into biomass accumulation and merchantable volume.

The absence of decoupling between diameter and biomass responses further suggests that enhanced growth under silvicultural interventions was efficiently converted into carbon storage and volume increment, as documented in long-term tropical silvicultural experiments (De Graaf et al. 1999; Peña-Claros et al. 2008; Schwartz et al. 2013). From a management perspective, the alignment among diameter, biomass, and volume gains is particularly relevant, as diameter growth is the primary operational criterion for defining cutting cycles and minimum cutting diameters, indicating that

treatments accelerating DBH growth also promote faster recovery of timber stocks and carbon pools (Putz et al. 2001; Gourlet-Fleury et al. 2013; Roopsind et al. 2017; Sist et al. 2021).

4.4. Structural consequences of silvicultural treatments

Silvicultural treatments produced clear and persistent effects on the diameter structure of *T. glauca* populations, demonstrating that growth responses observed at the individual level translated into measurable changes in population-level structure over time. Enrichment planting resulted in a marked shift toward intermediate and larger diameter classes by 2023, whereas the control treatment remained dominated by small-diameter individuals, with limited upward progression along the size distribution. The tending treatment exhibited an intermediate structural pattern, confirming that partial competitive release can promote size differentiation but is insufficient to rapidly restructure populations when regeneration density and spatial configuration are constrained.

These contrasting diameter class distributions indicate that silvicultural interventions not only accelerate individual growth but also modify demographic trajectories by increasing the proportion of trees advancing into higher size classes, a prerequisite for reducing time to commercial sizes (Rozendaal et al. 2010; Schwartz et al. 2013). From an ecological perspective, such structural reorganization reflects treatment-induced changes in competition intensity, spacing, and growth history, which amplify size asymmetry and promote vertical differentiation within gaps (Swaine and Whitmore 1988; Fredericksen and Putz 2003).

From a management perspective, the observed structural shifts are particularly relevant, as diameter structure underpins future harvest potential and yield regulation. Faster accumulation of individuals in larger size classes under enrichment planting suggests greater predictability in timber recovery compared to reliance on natural regeneration alone (van Gardingen et al. 2006; Gourlet-Fleury et al. 2013; Roopsind et al. 2017). These results reinforce that post-harvest silvicultural treatments shape forest structure in ways that extend beyond short-term growth gains, establishing lasting demographic and structural conditions that are critical for sustainable forest management (Putz et al. 2001; Sist et al. 2021).

4.5. Implications of growth projections for rotation length and forest management

Growth projections derived from observed post-establishment increments indicate that silvicultural interventions substantially modify the time required for *T. glauca* to reach the minimum cutting diameter of 50 cm, with direct implications for rotation length in managed tropical forests. When adjusted to the full experimental timeline (accounting for the establishment of the logging gaps in 2006) the projected time to commercial diameter averaged approximately 58 years under enrichment planting, compared to 96 years under tending and about 178 years under control conditions. These contrasts highlight the magnitude by which post-harvest silviculture alters recovery trajectories, particularly when compared to conventional reduced-impact logging (RIL) systems that rely solely on natural regeneration.

When expressed in terms of operational cutting cycles, assuming an average cycle length of 30 years, these projections translate into markedly different management outcomes. Enrichment planting would require approximately two cutting cycles (≈ 1.9 cycles) for *T. glauca* to reach commercial size, whereas tending would require just over three cycles (≈ 3.2 cycles), and control conditions would extend recovery to nearly six cycles (≈ 6.0 cycles). This comparison underscores the limited feasibility of relying on natural regeneration alone to restore commercial stocks within biologically and economically realistic planning horizons, a conclusion repeatedly emphasized in long-term studies of Amazonian forest management (Valle et al. 2007; Roopsind et al. 2017; de Avila et al. 2017; Sist et al. 2021).

4.6. Uncertainty, model assumptions, and limitations

As in other applied forest growth studies, projected trajectories implicitly assume that the structural and competitive conditions are broadly maintained through time, concerning stand structure, neighborhood competition, and management continuity (Vanclay 1994; Gourlet-Fleury et al. 2013). To balance biological realism with data availability, we adopted a hybrid projection framework. It combines empirically observed medium-term growth with a conservative reduction in diameter increment at larger sizes, avoiding fully asymptotic growth models that require extensive observations at advanced diameter classes and are prone to unsupported extrapolation when such data are lacking (Rozendaal et al. 2010; Ferreira et al. 2020).

Although empirical observations ≥ 35 cm in DBH were unavailable, this limitation does not compromise the primary objective of the analysis, which was to estimate the time required to reach the minimum cutting diameter rather than to characterize long-term asymptotic growth behavior (van Gardingen et al. 2006; Ferreira et al. 2020). By constraining projections to biologically plausible trajectories and truncating them at the commercial threshold, the approach emphasizes management relevance while maintaining transparency regarding assumptions and uncertainty, in line with current recommendations for applied modeling in tropical forest management (Sist et al. 2021).

4.7. Management and policy implications for tropical production forests

From a policy perspective, these results highlight the need to incorporate intensive silvicultural treatments, such as enrichment planting, into public forest management policies, including national forest concession systems. Modelling studies of Amazonian concessions indicate that reduced-impact logging (RIL) alone fails to ensure sustainable commercial volume recovery within realistic cycles, emphasising the importance of post-harvest interventions to meet certification requirements (e.g., FSC) and long-term planning needs (Sist et al. 2021; DeArmond et al. 2023, 2025). Incentives for adopting enrichment planting—such as subsidies for native seedling production, technical training, and continuous monitoring—could accelerate the transition toward more sustainable practices, reducing illegal deforestation and enhancing the resilience of managed forests to climate change.

In summary, the routine integration of enrichment planting into RIL systems represents a decisive strategy for reconciling timber production with conservation in the Amazon, ensuring that polycyclic management not only maintains but enhances the ecological and economic functionality of productive tropical forests over the long term (van Gardingen et al. 2006; Rozendaal et al. 2010; Neves et al. 2019; Ferreira et al. 2020).

5. CONCLUSION

This study demonstrates that post-harvest silvicultural interventions fundamentally alter growth trajectories, structural development, and recovery time of *Tachigali glauca* in managed Amazonian forests. Enrichment planting consistently enhanced diameter growth, biomass accumulation, and volume increment, translating individual-level gains into accelerated population-level structural advancement and substantially shortening the time required to reach commercial diameter. When expressed in operational terms, these effects reduced recovery to approximately two cutting cycles, compared to more than three cycles under tending and nearly six cycles under control conditions. This reinforces evidences that reduced-impact logging alone is insufficient to restore commercial stocks within conventional rotation lengths. By showing that growth responses are governed primarily by persistent structural controls imposed by management, this study provides a management-oriented framework linking empirical growth data to rotation planning and yield recovery. Overall, the results highlight enrichment planting as a key mechanism for enhancing the predictability, sustainability, and long-term viability of tropical forest management under fixed cutting cycles.

Declarations

Declaration of interest statement: The authors have no competing interests to declare that are relevant to the content of this article.

Author Contribution

R.L.P.N. was responsible for conceptualization, data curation, formal analysis, investigation, visualization and writing the original draft of the manuscript, as well as writing review and editing. G.S. contributed to conceptualization, methodology, investigation, supervision, writing review and editing. J.C.A.L. contributed to conceptualization, methodology, investigation, writing review and editing. All authors reviewed and approved the final manuscript.

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Data availability:

The data of this study are available from the corresponding author upon reasonable request.

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Figures

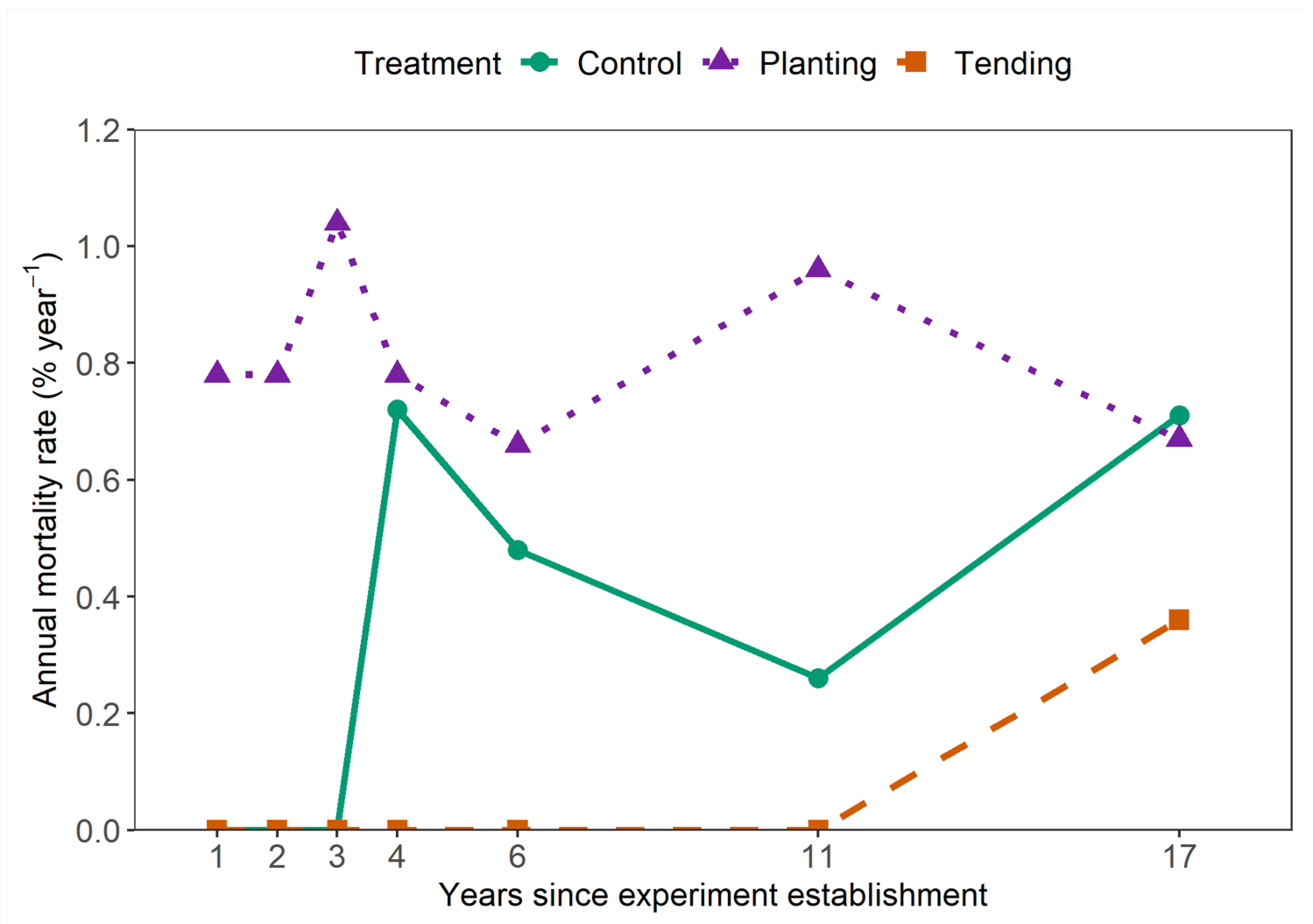


Figure 1

Temporal variation in annual mortality rates (% year⁻¹) of *Tachigali glauca* under standard reduced-impact logging (control), tending of naturally established regeneration (tending), and enrichment planting (planting) treatments across 17 years following logging (2006–2023) in logging gaps of a managed forest in the eastern Amazon (Jari, Brazil)

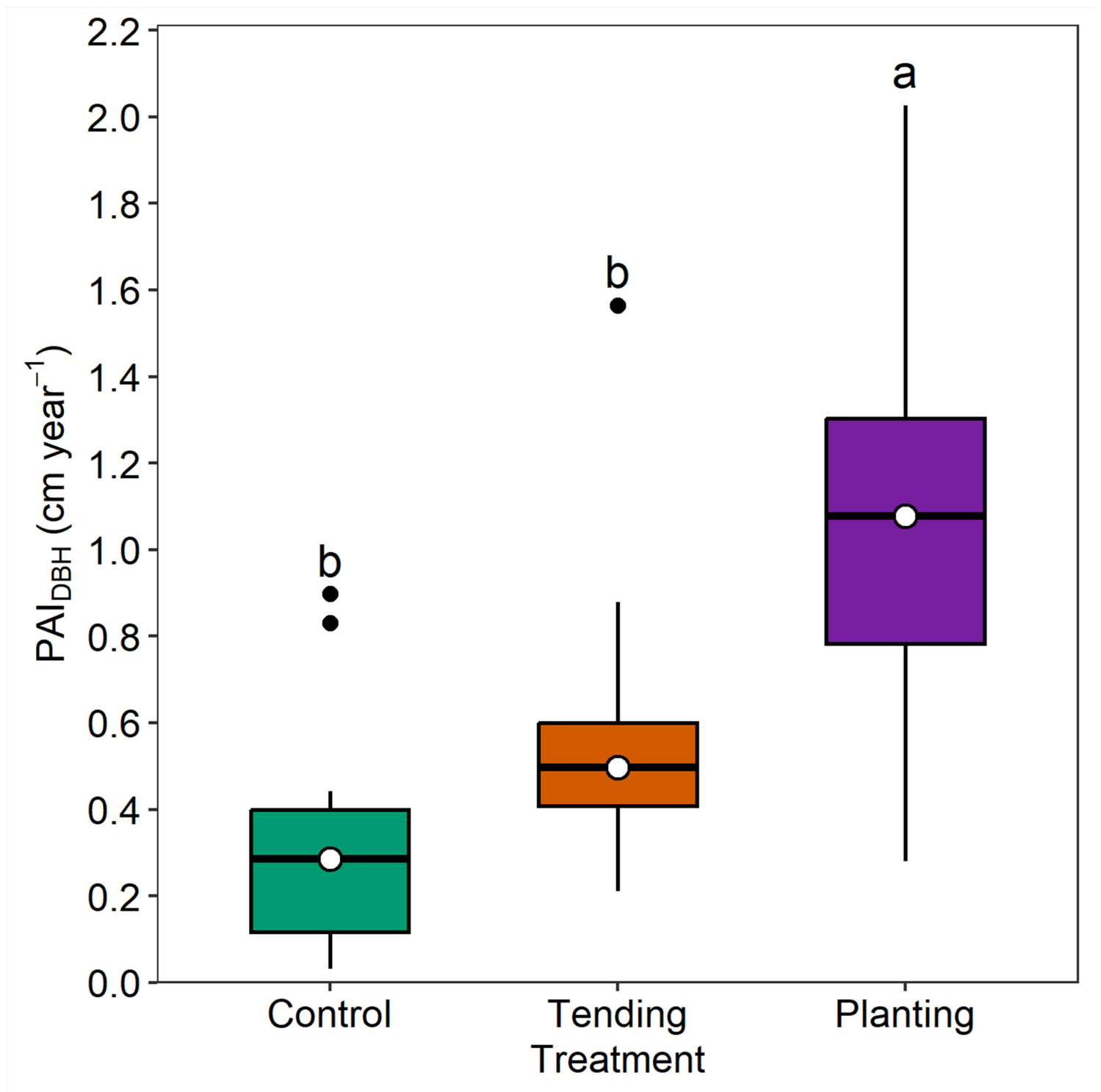


Figure 2

Periodic annual diameter increment (PAIDBH cm year⁻¹) of *Tachigali glauca* under standard reduced-impact logging (control), tending of naturally established regeneration (tending), and enrichment planting (planting) treatments between 2010 and 2023 in logging gaps of a managed forest in the eastern Amazon (Jari, Brazil). Boxes represent the interquartile range, horizontal lines indicate medians, and whiskers denote data dispersion. Different letters indicate significant differences among treatments according to Tukey's HSD test ($p < 0.05$)

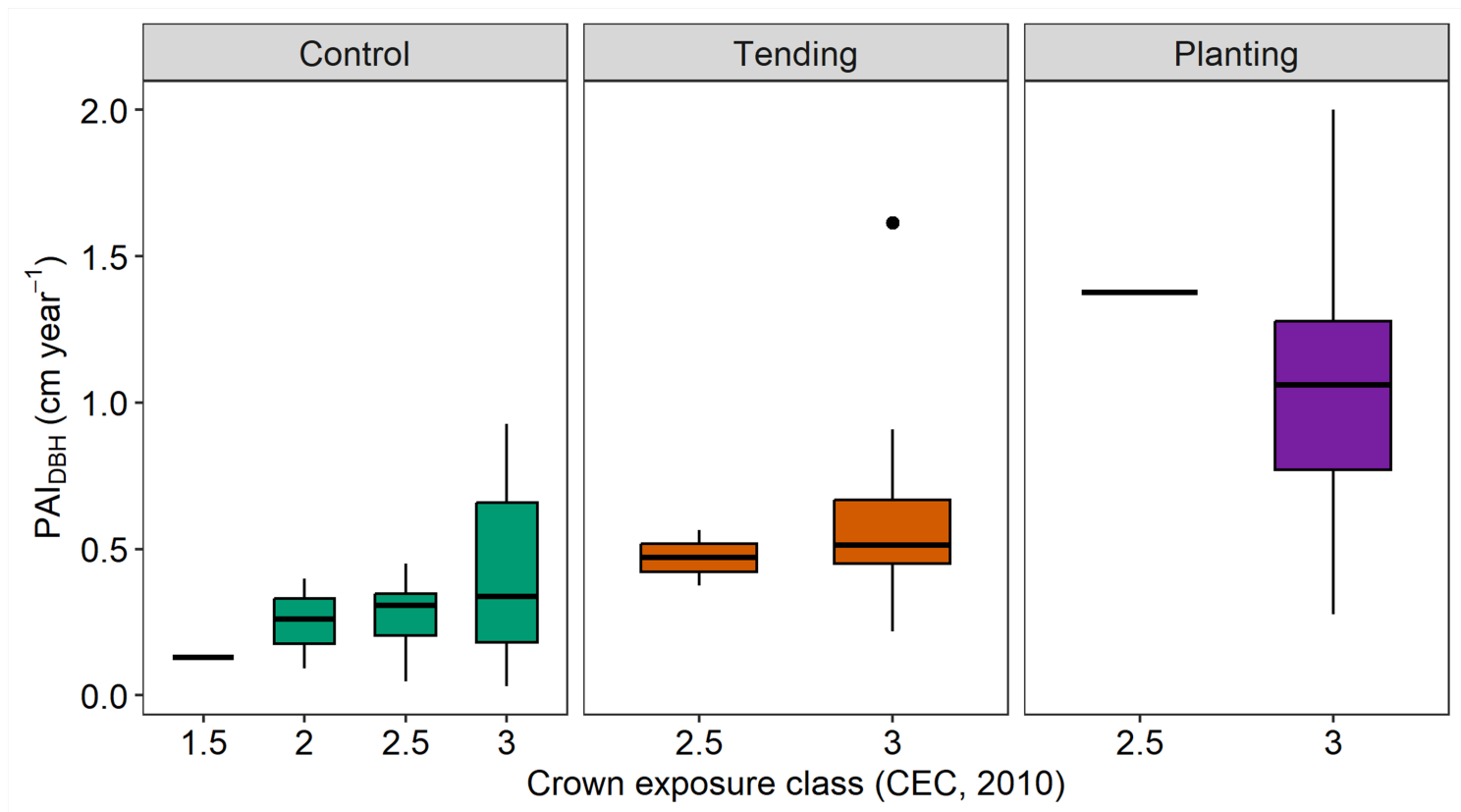


Figure 3

Periodic annual diameter increment (PAI_{DBH}, cm year⁻¹) of *Tachigali glauca* in relation to crown exposure class (CEC), adapted from Dawkins and Field (1978) and Clark and Clark (1992). Crown exposure classes 1.5–2.5 represent crowns receiving lateral light only, without direct vertical exposure, subdivided into low (1.5), intermediate (2.0), and high (2.5) lateral illumination. Class 3 represents crowns with partial vertical light exposure, with approximately 10–90% of the vertical crown projection exposed to direct radiation. Crown exposure was assessed in 2010 under three silvicultural treatments: standard reduced-impact logging (control), tending of naturally established regeneration (tending), and enrichment planting (planting). Growth responses correspond to the 2010–2023 interval in logging gaps of a managed forest in the eastern Amazon (Jari, Brazil). Boxes represent the interquartile range, horizontal lines indicate medians, and whiskers denote data dispersion

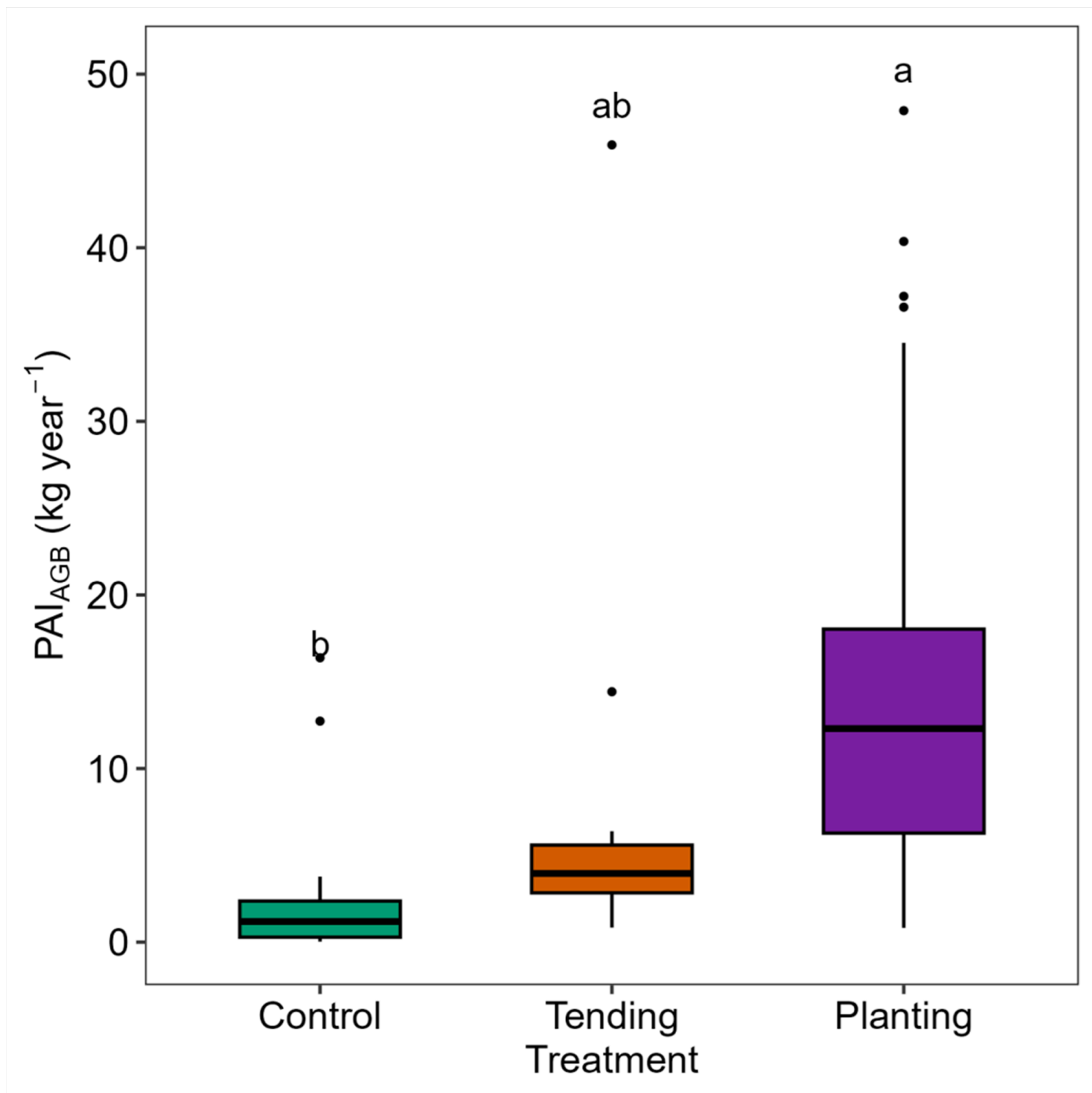


Figure 4

Annual increment in aboveground biomass (PAI_{AGB} , $kg\ yr^{-1}$) of *Tachigali glauca* under different silvicultural treatments (control, tending, and planting). Boxes represent the interquartile range, the horizontal line indicates the median, whiskers correspond to $1.5\times$ the interquartile range, and points denote individual observations (outliers). Different letters above boxes indicate significant differences among treatments based on Tukey's HSD post hoc test following ANOVA on log-transformed data ($p < 0.05$)

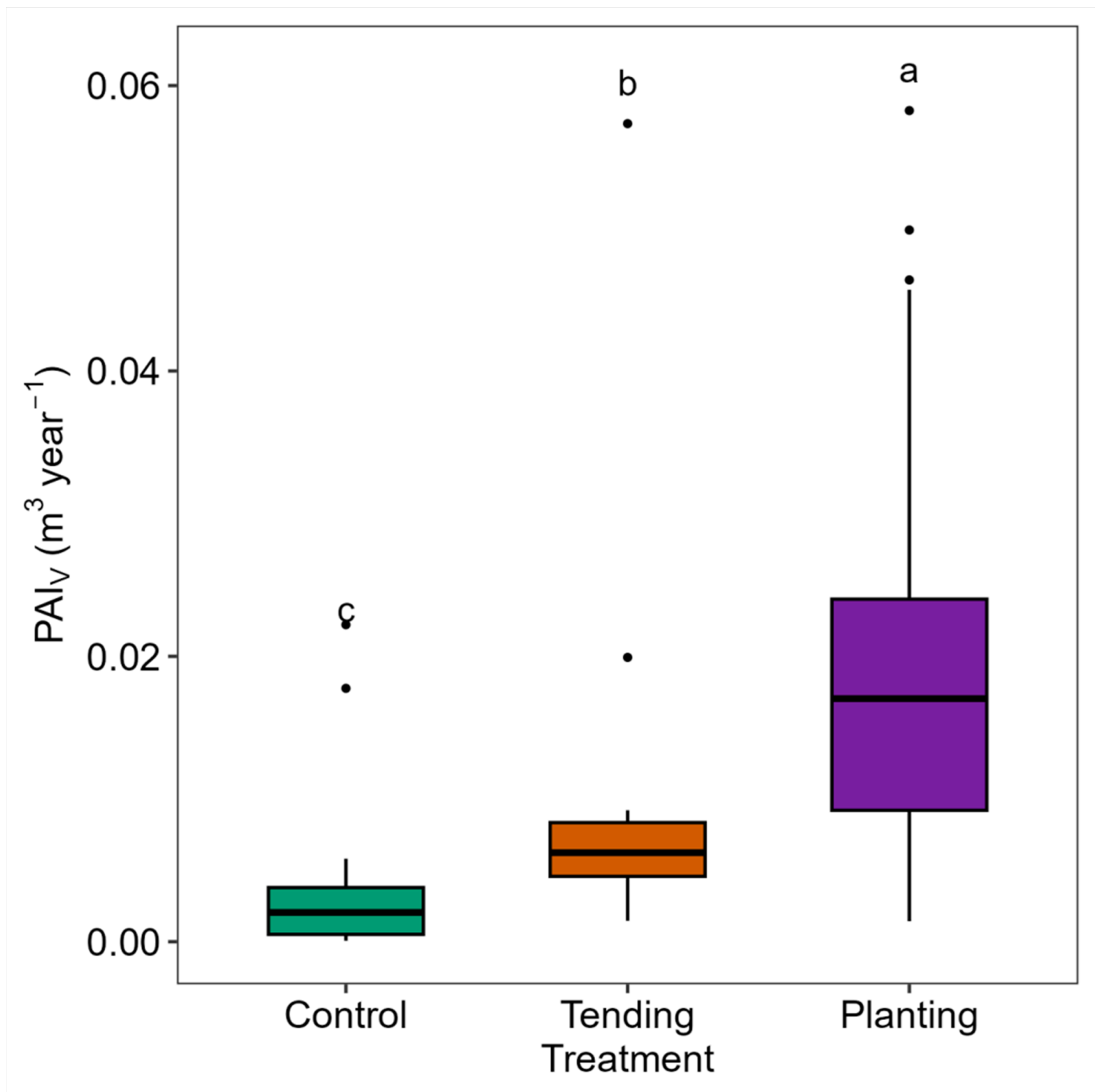


Figure 5

Annual periodic increment in stem volume (PAI_V , $m^3 year^{-1}$) of *Tachigali glauca* under different silvicultural treatments. Boxplots represent the median, interquartile range, and minimum–maximum values (excluding outliers). Different letters indicate significant differences among treatments according to Tukey's HSD test ($p < 0.05$), based on ANOVA applied to Box–Cox transformed data

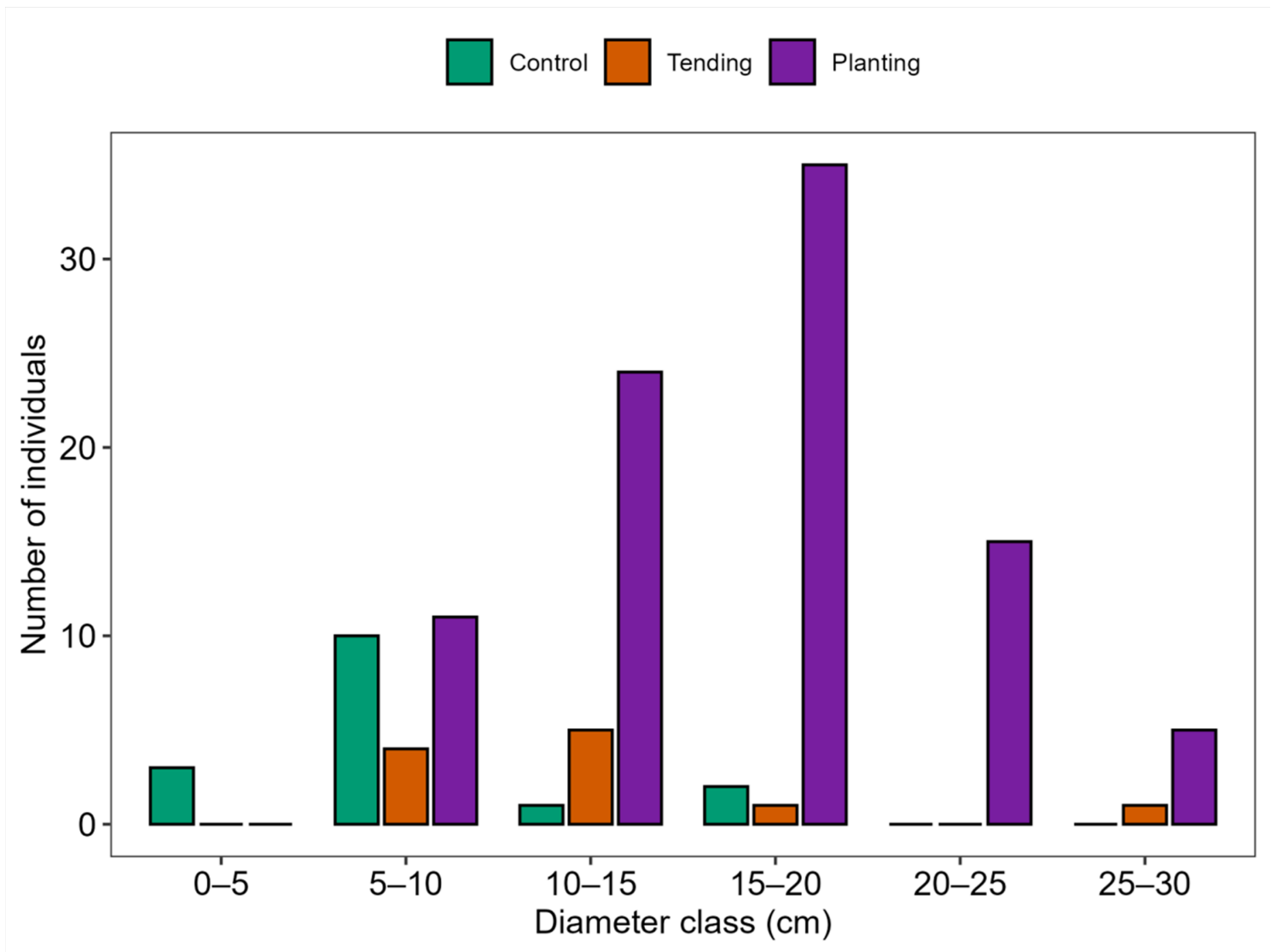


Figure 6

Diameter class distribution of *Tachigali glauca* individuals in 2023 under different silvicultural treatments (Control, Tending, and Enrichment Planting). Bars represent the number of individuals per 5-cm diameter class

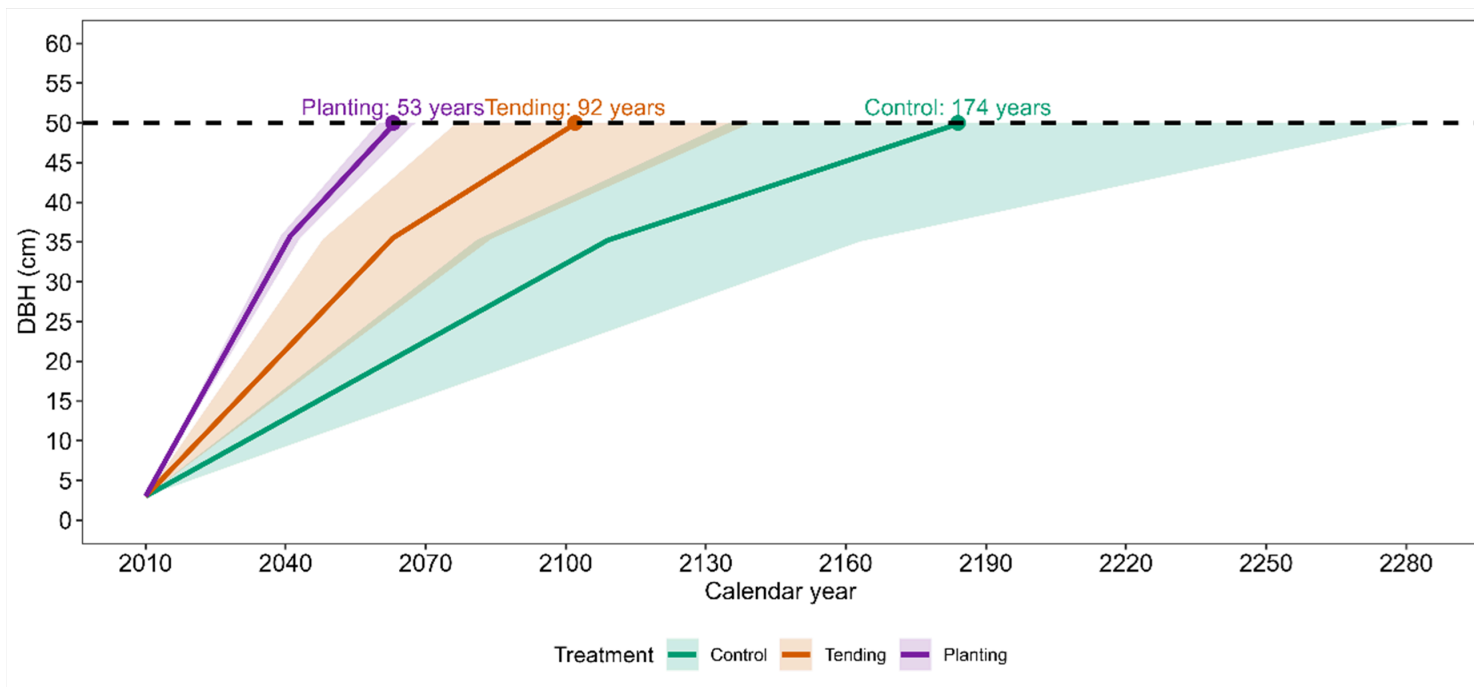


Figure 7

Projected diameter growth trajectories of *Tachigali glauca* under control, tending, and enrichment planting treatments, based on bootstrap estimates of periodic annual increment in diameter (PAI_{DBH}). Solid lines represent mean projected diameter growth, while shaded areas indicate 95% confidence intervals derived from 1,000 bootstrap resamples. Projections incorporate a reduced growth rate beyond 35 cm DBH to account for ontogenetic growth deceleration. The horizontal dashed line indicates the minimum cutting diameter (50 cm)