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RELATIONSHIP BETWEEN GROWTH, RESIN DUCTS, AND GUM-RESIN PRODUCTIVITY IN *Pinus caribaea* var. *hondurensis* BARR. & GOLF.

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ABSTRACT

The genus *Pinus* has broad economic relevance in Brazil, both for timber production and for oleoresin extraction, an activity in which the country ranks among the world's leading producers. *Pinus caribaea* var. *hondurensis* Barr. & Golf. is one of the tropical species with the greatest potential for multiple uses, distinguished by its vigorous growth and resin-producing viability. This study aimed to evaluate its growth in diameter at breast height (DBH), the number of resin canals (NRC), gum resin productivity (GRP), and the relationship among these traits in 31 half-sib progenies of this species, aiming to identify materials with potential for breeding programs. The experiment was established in a randomized complete block design, with thirty replications and one plant per plot, in Lavras, Minas Gerais state, Brazil. For the evaluation of DBH (cm), NRC, and GRP (kg tree^{-1}), only three replications were considered in this study, with DBH and NRC assessed at eight years and GRP at nine years after planting. The data were subjected to analysis of variance (ANOVA) and the Scott-Knott test ($p < 0.10$), in addition to Pearson correlation analysis. The results revealed significant phenotypic variability among the progenies for all the analyzed traits. The superior progenies were identified for DBH, NRC, and GRP, highlighting the potential for genetic gains. The correlation between DBH and NRC was moderate (0.74), while correlations with GRP were low (<0.32), indicating its multifactorial nature. The study demonstrates phenotypic variability among progenies and low correlation among the evaluated traits, indicating the need for independent selection strategies to maximize gains in a breeding program.

Keywords: Forest breeding, Progeny, Phenotypic variability

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RELAÇÃO ENTRE CRESCIMENTO, CANAIS RESINÍFEROS E PRODUTIVIDADE DE GOMA-RESINA EM *Pinus caribaea* var. *hondurensis* BARR. & GOLF.

RESUMO O gênero *Pinus* possui ampla relevância econômica no Brasil, tanto para produção de madeira quanto para extração de goma-resina, atividade em que o país se destaca como um dos principais produtores mundiais. *Pinus caribaea* var. *hondurensis* Barr. & Golf. é uma das espécies tropicais com maior potencial para uso múltiplo, destacando-se pelo crescimento vigoroso e viabilidade resinífera. Este estudo teve como objetivo avaliar o crescimento em diâmetro à altura do peito (DAP), o número de canais resiníferos (NCR), a produtividade de goma-resina (PGR) e a relação entre eles, em 31 progênies de meios-irmãos dessa espécie, visando identificar materiais com potencial para programas de melhoramento. O experimento foi instalado em delineamento de blocos completos casualizados, com trinta repetições e uma planta por parcela, em Lavras, estado de Minas Gerais. Para a avaliação do DAP (cm), do NCR e da PGR (kg árvore^{-1}) neste estudo, foram consideradas apenas três repetições, sendo DAP e NCR avaliados aos oito anos e PGR aos nove anos após o plantio. Os dados foram submetidos à análise de variância (ANAVA) e ao teste de Scott-Knott ($p < 0,10$), além da análise de correlação de Pearson. Os resultados revelaram variabilidade fenotípica significativa entre as progênies em todas as características analisadas. Foram identificadas progênies superiores para DAP, NCR e PGR, destacando o potencial para ganhos genéticos. A correlação entre DAP e NCR foi moderada (0,74), enquanto as correlações com PGR foram baixas (<0,32), indicando seu caráter multifatorial. O estudo aponta variabilidade fenotípica entre as progênies e baixa correlação entre as variáveis em estudo, demonstrando a necessidade de estratégias de seleção independentes para maximização de ganhos com a seleção em um programa de melhoramento.

Palavras-Chave: Melhoramento florestal, Variabilidade fenotípica, Resinagem

1. INTRODUCTION

In Brazil, the cultivation of species from the *Pinus* genus gained prominence from the second half of the 20th century onward, driven by public reforestation policies and tax incentives aimed at the forestry sector (SFB, 2025). Among the main factors that contributed to the widespread adoption of these species are their rapid growth, high wood productivity, and ability to adapt to different edaphoclimatic conditions (dos Santos et al., 2021).

Currently, species of the genus *Pinus* are widely used in the timber, pulp, and paper industries, reflecting their well-established economic importance in Brazil. In parallel with these uses, some species also show potential for gum resin extraction, an activity considered secondary, but which places Brazil as the world's largest exporter and second-largest producer, surpassed only by China (ARESB, 2025; Candaten et al., 2021; Zhang et al., 2023). The species *Pinus caribaea* var. *hondurensis* Barr. & Golf. is one of the most cultivated in tropical regions, being commercially valued for the combination of high wood yield and resin production potential (de Lima et al., 2021; dos Santos et al., 2021). Its gum resin is used in the production of rosin, turpentine, and other raw materials for the chemical, pharmaceutical, and biofuel industries (Brito et al., 1980; ARESB, 2025).

The diameter growth of *P. caribaea* var. *hondurensis* is influenced by genetic, climatic, and management factors, and may reach annual increments between 2 and 3 cm in diameter at breast height (Silva et al., 2019; Oliveira et al., 2024). This growth directly reflects cambial activity and is associated with tree vigor, favoring, for example, the formation of resiniferous structures - resin canals - responsible for the transport and exudation of gum resin, which constitutes a defense mechanism in conifers (Ananías et al., 2010; Ferreira & Tomazello-Filho, 2012). Studies indicate that diameter growth may be positively correlated with resin canal density and gum resin yield (Ferreira & Tomazello-Filho, 2012; Leggate et al., 2020; López-Alvarez et al., 2023).

Despite the recognized economic and biological importance of this species, studies that simultaneously integrate morphometric, anatomical, and productive variables at the progeny level under tropical conditions are still scarce. The development of research addressing these variables is relevant to tropical forestry, as the identification of progenies with superior morphometric, anatomical, and productive performance may support the selection of more suitable genetic materials for resin exploitation in commercial plantations. Therefore, the objective of this study was to evaluate the diameter at breast height (cm), the number of resin canals, the gum resin productivity (kg tree^{-1}), and the relationship among these traits in thirty-one progenies of *P. caribaea* var. *hondurensis* under field conditions.

2. MATERIAL AND METHODS

2.1 Experimental characterization

The experiment was established in September 2015 in Lavras, state of Minas Gerais, Brazil (21°14'19.6"S; 44°58'28.5"W) (Figure 1). The area is located in an ecotone region between the Cerrado and the Atlantic Forest and has dystrophic Haplic Cambisol soil (Embrapa, 2018). The climate is classified as high-altitude tropical with mild summers (Cwb), according to the Köppen–Geiger classification, with a mean annual temperature of 19.6°C and mean annual precipitation of 1,511 mm (INMET, 2025).

The progenies of *P. caribaea* var. *hondurensis* were obtained from open-pollinated parent trees located in commercial plantations of Resineves Agronegócios, in Itapeva. The company itself produced the seedlings in 55 cm³ tubes filled with

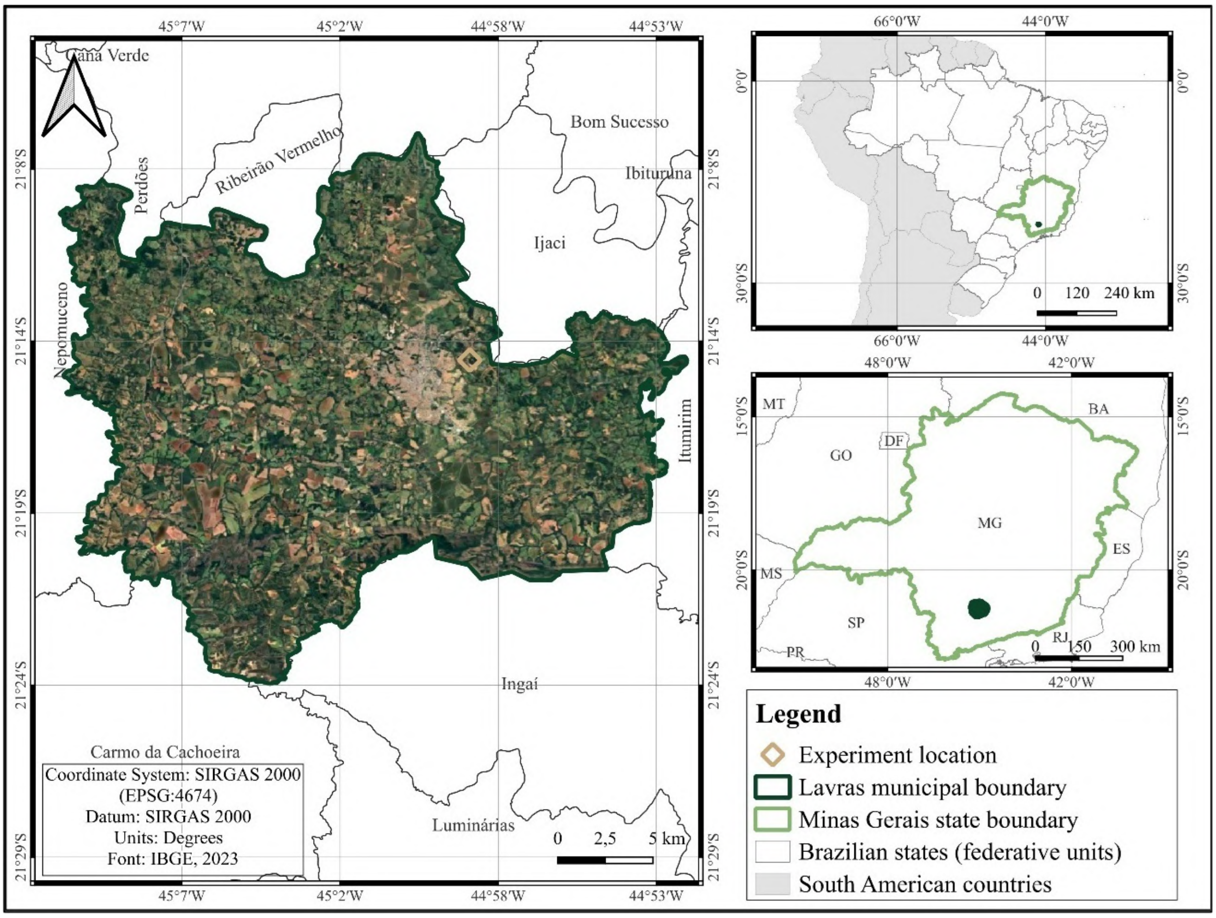


Figure 1. Map of the experimental area with the half-sib progenies of *P. caribaea* var. *hondurensis*, in Lavras, MG, Brazil

Figura 1. Mapa da área experimental com as progênies de meios-irmãos de *P. caribaea* var. *hondurensis*, em Lavras - MG commercial substrate. The progeny test was established following the methodology described by Nieri et al. (2022), using a randomized complete block design composed of thirty-one half-sib progenies of *P. caribaea* var. *hondurensis* (P18, P19, P20, P21, P22, P24, P25, P26, P28, P30, P33, P34, P35, P37, P39, P40, P41, P43, P44, P46, P49, P50, P52, P54, P55, P57, P58, P59, P61, P63, and P68), with thirty replications containing one plant per plot. However, due to operational constraints, only data from three replications were considered for the evaluations performed in this study.

2.2 Evaluation of DBH, number of resin canals, and gum resin production

The diameter at breast height (DBH) and the number of resin canals (NRC) were evaluated eight years after planting. DBH (cm) was measured using a tree caliper. The number of resin canals per mm² was determined according to the following procedure:

Sample collection - Four samples were collected from the trunk of each tree at breast height (1.30 m). Cylindrical samples measuring 0.5 cm in diameter × 6 cm in length were obtained using an increment borer inserted perpendicular to the main axis of the trunk. For the sample collection, the north, south, east, and west positions of the trunk were considered, maintaining standardization for all the trees used in the experiment. The collected samples were placed in properly identified permeable containers and kept immersed in distilled water until the laboratory processing (Figure 2A).

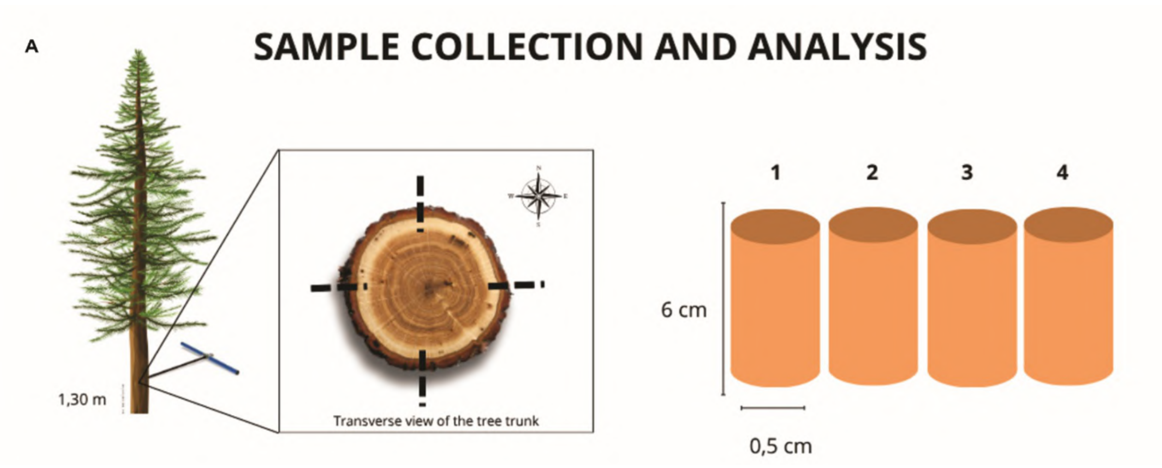
Sample processing - The samples were processed at the Wood Anatomy Laboratory of the Federal University of Lavras, Minas Gerais state, Brazil. Fragments measuring 1 cm were removed from each cylindrical sample (from the first centimeter immediately after the bark) and sectioned into 10 µm thick transverse sections using a Leica SM 2010R sliding microtome (Leica Biosystems, Wetzlar, Germany). To characterize each tree, four fragments (one from each position — north, south, east, and west) measuring 0.5 cm × 1 cm were arranged on a microscope slide (Figure 2B).

Staining of the sections - The sections were cleared with a sodium hypochlorite solution, stained with safranin, dehydrated through an ethanol series (20%, 50%, 70%, 80%, and 100%) combined with n-butyl acetate (25%, 50%, 75%, and 100%) (Johansen, 1940), and mounted with Entellan® synthetic resin.

Image acquisition - The images were obtained and analyzed using a Zeiss Primo Star HAL/LED light microscope (Carl Zeiss, Oberkochen, Germany) coupled to an Opton digital camera at 4× magnification.

Photographs - Vectorized images were produced using CorelDRAW 3.0 software to illustrate the resin canals in the obtained sections.

Canal quantification - In the photographs, the number of canals per mm² was randomly quantified within the fragment



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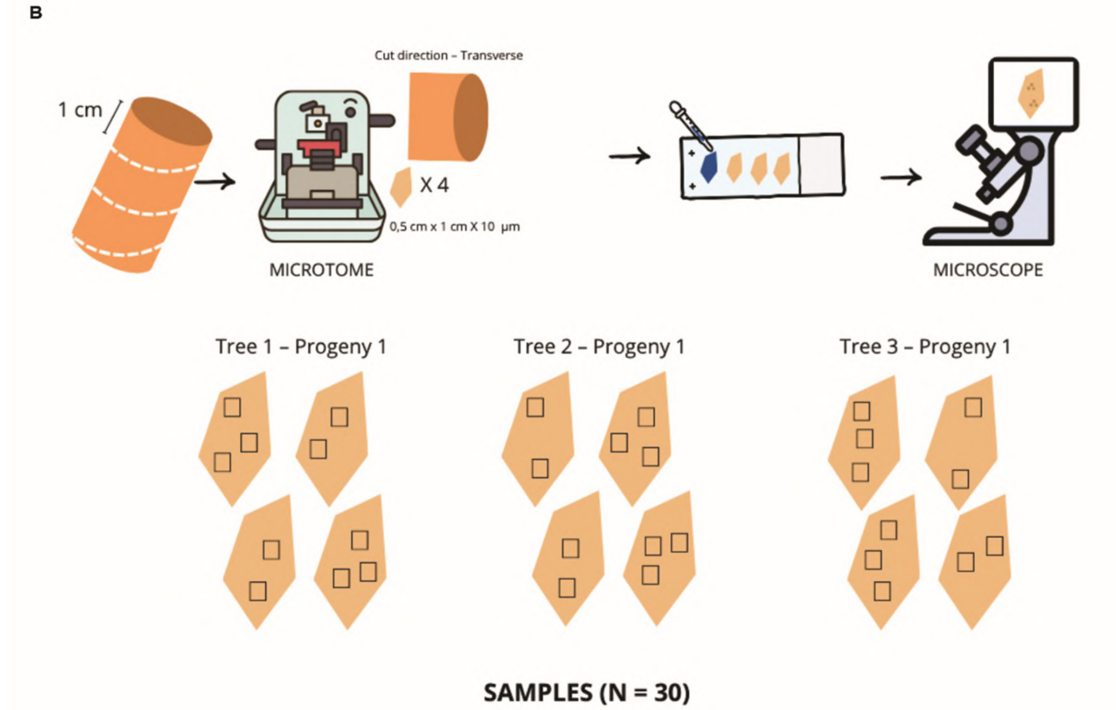

Figure 2. Characterization of the collection and processing stages of *P. caribaea* var. *hondurensis* samples for quantification of the number of resin canals. A – Field sample collection. B – Sample processing and slide preparation

Figura 2. Caracterização das etapas de coleta e processamento das amostras de *P. caribabea* var. *hondurensis* para quantificação do número de canais resiníferos. A - Coleta das amostras em campo. B - Processamento das amostras e preparo das lâminas

without overlap using a 1 mm × 1 mm template. For each tree, 30 samples were collected, and the mean number of canals per mm² was subsequently calculated.

The mean number of canals per mm² was extrapolated considering the sectional area (Equation 1) of the first centimeter surrounding the tree trunk immediately beneath the bark (Figure 3), given by:

$$Ac = \pi(R^2 - r^2) \quad \text{(Eq. 1)}$$

Where: Ac = sectional area of the ring (mm²); π = 3.1416; R = outer radius; r = inner radius.

Subsequently, the number of resin canals (NRC) for the respective sectional area was obtained using Equation 2:

$$\frac{Sectional\ area(mm^2)\ x}{Mean\ number\ of\ canals\ per\ mm^2} \quad \text{(Eq. 2)}$$

The evaluation of gum resin productivity (GRP - kg tree⁻¹) was carried out at nine years of age over six months (November 2024 to May 2025). The trees with a diameter equal to or greater than 15 cm were selected for resin tapping on one side of the trunk, following the methodology adapted from Lazarotto et al. (2023).

2.3 Statistical analyses

After obtaining the data, the analysis of variance (ANOVA) was performed and, when significant differences among progenies were detected, mean comparisons were carried out using the Scott-Knott test ($p < 0.10$).

The percentage of coincidence among progenies (considering the variables GRP and DBH; GRP and NRC) within the best-performing group(s) was determined using Equation 3:

$$PC(\%) = \left(\frac{Number\ of\ coincident\ progenies\ among\ the\ variables\ in\ group\ (a)}{Total\ number\ of\ progenies\ in\ group\ (a)}\right) x\ 100 \quad \text{(Eq. 3)}$$

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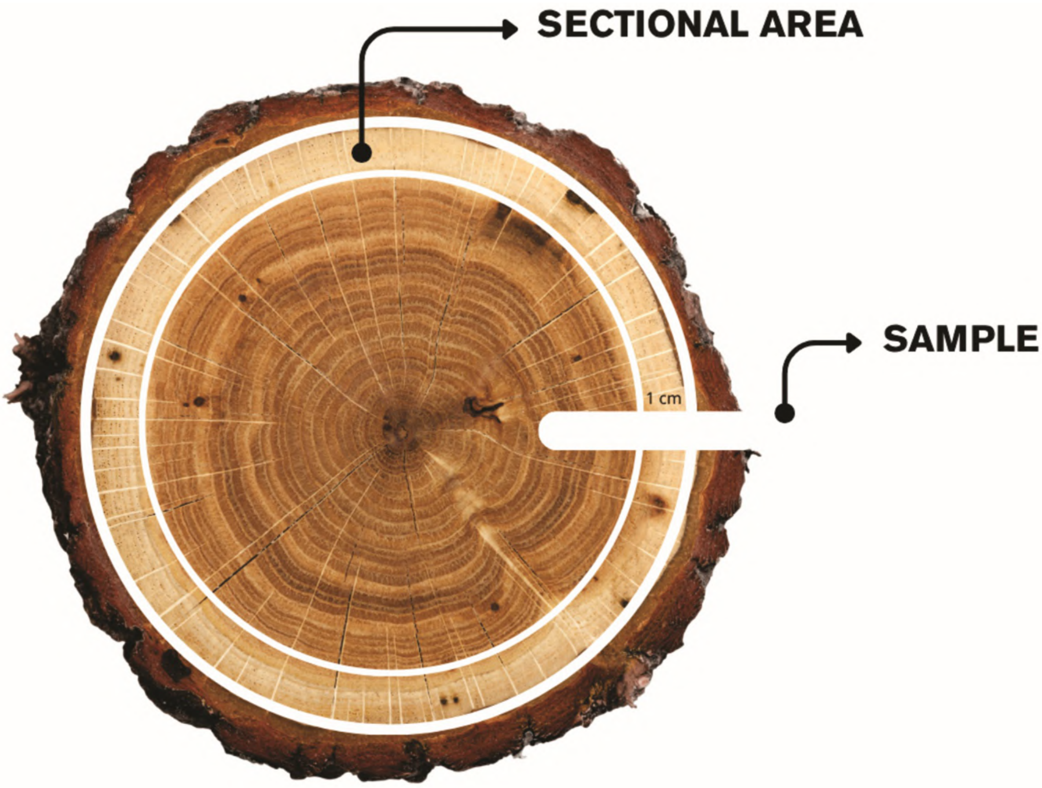


Figure 3. Characterization of the sectional area of the first centimeter surrounding the tree trunk, immediately beneath the bark, for quantification of the number of resin canals in *P. caribaea* var. *hondurensis*

Figura 3. Caracterização da área seccional do primeiro centímetro que circunda o tronco da árvore, imediatamente após a casca, para quantificação do número de canais resiníferos em *P. caribaea* var. *hondurensis*

Pearson's correlation was determined for the variables under study. All statistical procedures were performed using the R software (R Core Team, 2024), and the graphs were generated using the ggplot2 package (Wickham et al., 2026).

3. RESULTS

The analysis of variance revealed statistically significant differences among the progenies of *P. caribaea* var. *hondurensis* for the evaluated traits: DBH (cm), NRC, and GRP (kg tree^{-1}). The observed significance ($p < 0.05$ for DBH and NRC; $p < 0.10$ for GRP) indicates the presence of relevant phenotypic variability among the progenies, highlighting the potential for gains through selection in genetic improvement programs. The mean values of 22.9 cm for DBH (Table 2), 14,582.12 for NRC, and 1.03 kg tree^{-1} for GRP were observed (Table 1).

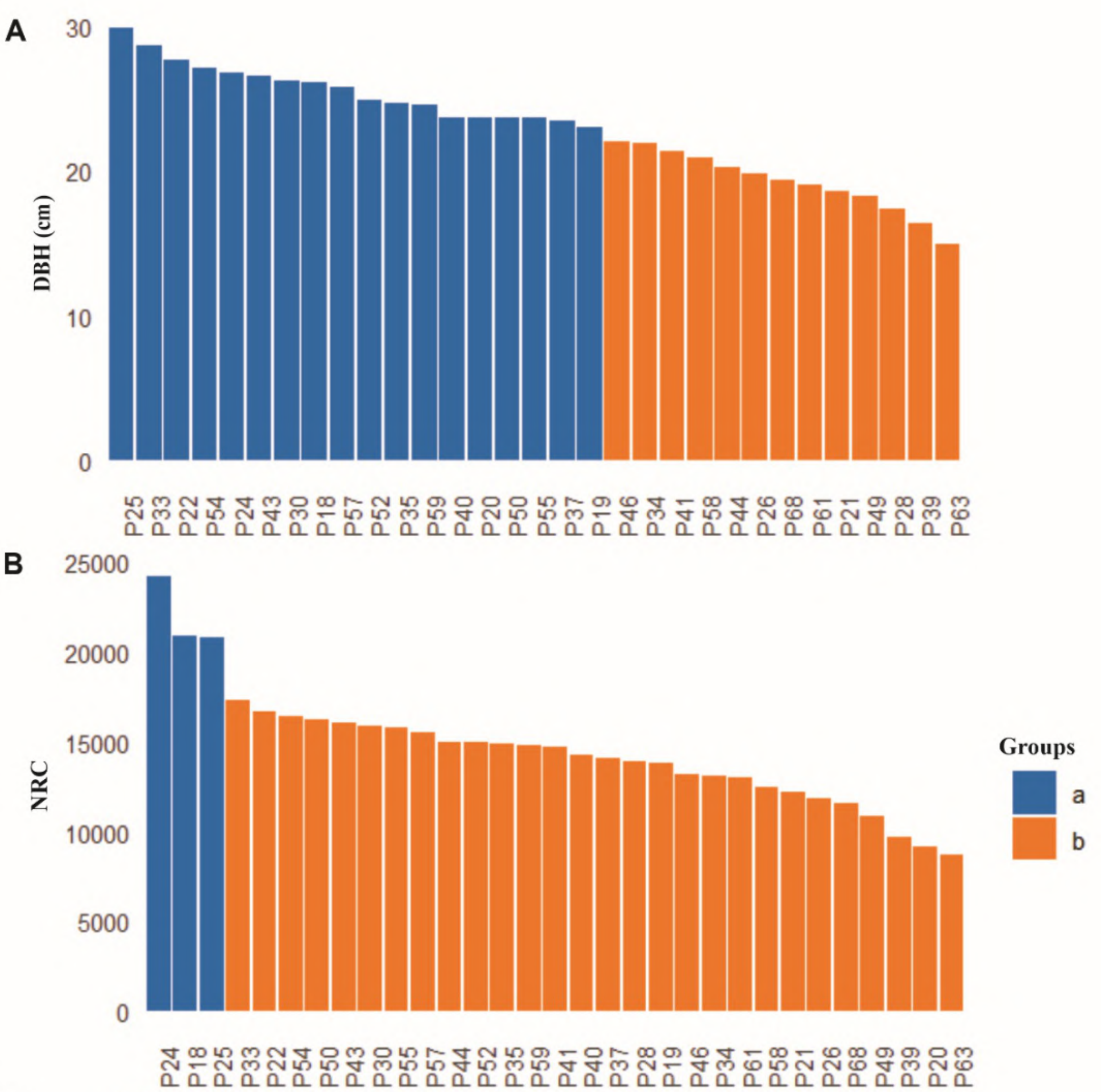
Based on the detected differences, it was possible to form two homogeneous groups among the 31 progenies of *P. caribaea* var. *hondurensis* evaluated for DBH (cm), NRC, and GRP (kg tree^{-1}). For DBH (Figure 4A), the mean values ranged from approximately 17 cm to 30 cm, with emphasis on progenies P18, P19, P20, P22, P24, P25, P30, P33, P35, P37, P40, P43, P50, P52, P54, P55, P57, and P59, which composed the superior group ("group a"), demonstrating the potential of these families for the growth increase.

The anatomical visualization of the transverse wood sections allowed the identification of longitudinal resin canals, associated epithelial cells, and other xylem structures (Figure 5). Regarding NRC (Figure 4B), the mean values showed wide variation, with progenies P18, P24, and P25 composing the superior group, presenting values greater than 20,000 canals in the

Table 1. Summary of the analysis of variance for DBH (cm), NRC (in sectional area), and GRP (kg tree⁻¹) of *P. caribaea* var. *hondurensis* progenies, in Lavras, MG, Brazil
Tabela 1. Resumo da análise de variância para o DAP (cm), NCR (em área seccional) e PGR (kg árvore-¹) de progênies de *P. caribaea* var. *hondurensis*, em Lavras – MG

Source of variation	DF	Mean Squares		
		DBH (cm)	NRC (-)	GRP (kg tree⁻¹)
Blocks	2	17,985^{ns}	3769,686 ^{ns}	0,100 ^{ns}
Progenies	30	41,953*	33168,823*	0,350**
Residuals	60	22,603	14159,39	0,228
Total	92	-	-	-
Mean	-	22,9	14582,12	1,03
CV (%)	-	20,77	25,8	46,42

DF = degrees of freedom; CV (%) = coefficient of variation; * = significant at the 5% probability level by the F test; ** = significant at the 10% probability level by the F test; ns = not significant.
GL = graus de liberdade; CV (%) = coeficiente de variação; * = significativo ao nível de 5% de probabilidade de erro pelo teste F; ** = significativo ao nível de 10% de probabilidade de erro pelo teste F; ns = não significativo.



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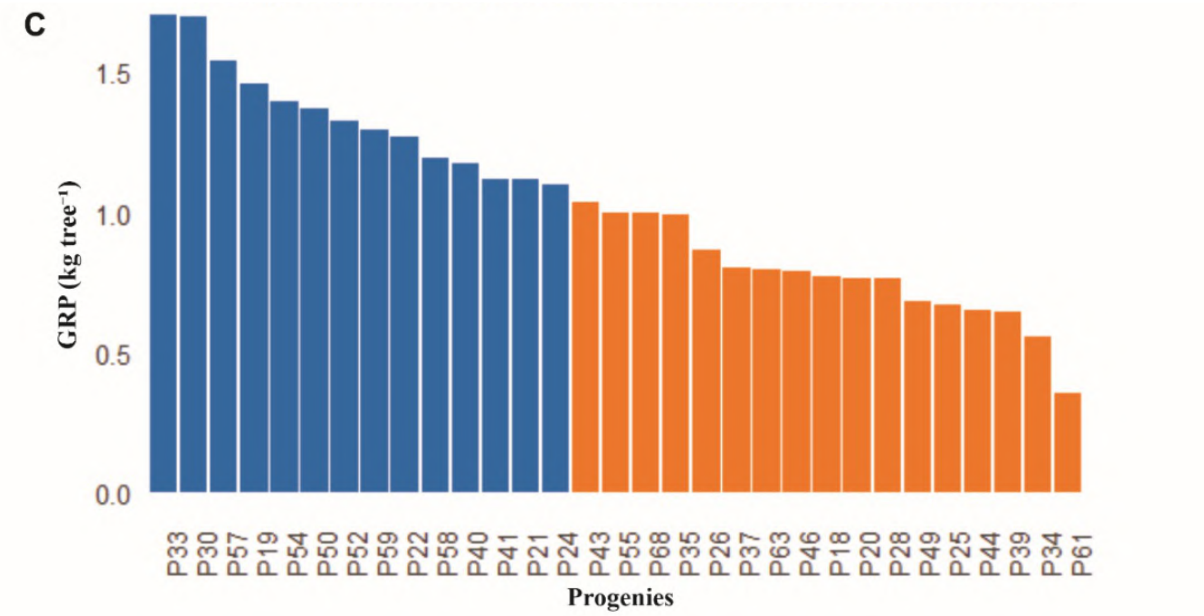

Figure 4. Mean values of DBH (cm), NRC, and GRP (kg tree^{-1}) of *P. caribaea* var. *hondurensis* progenies, in Lavras, MG, Brazil
Figura 4. Valores médios do DAP (cm), NCR e PGR (kg árvore^{-1}) das progênies de *P. caribaea* var. *hondurensis*, em Lavras - MG

sectional area of the first centimeter surrounding the trunk immediately beneath the bark, reinforcing the existence of anatomical variability with functional relevance for gum resin production.

For GRP (Figure 4C), a wide range of responses was also observed, with mean values varying from less than 0.5 kg tree^{-1} to more than 1.5 kg tree^{-1} over six months. Progenies P19, P21, P22, P24, P30, P33, P40, P41, P50, P52, P54, P57, P58, and P59 composed the group with the highest resin yield, demonstrating their productive superiority.

The coincidence analysis among progenies classified in the superior group ("a") for the different evaluated traits revealed distinct levels of overlap between groups, which complement the results obtained by Pearson's correlation analysis. It was observed that 100% of the progenies with the highest NRC also exhibited the highest DBH values (cm), a result consistent with the positive and moderately high correlation between these variables (0.74) (Figure 6). However, only 16.67% of the progenies with the highest DBH values (cm) coincided with those presenting the highest NRC, suggesting that although a high canal density may occur in individuals with good growth performance, it is not a mandatory condition.

Regarding GRP (kg tree^{-1}), 61.11% of the progenies with the highest DBH values (cm) were also among the most productive for resin yield, and 78.57% of the progenies with the highest GRP (kg tree^{-1}) coincided with those presenting the highest DBH values (cm), reflecting a trend of positive association between growth and resin production, although the correlation between these variables was of low magnitude (0.32) (Figure 6). In contrast, the relationship between NRC and GRP (kg tree^{-1}) showed even lower coincidence: only 33.33% of the progenies with the highest NRC were among the most productive ones, and only 7.14% of the most productive progenies coincided with those presenting the highest NRC. This low coincidence is consistent with the weak correlation observed between NRC and GRP (kg tree^{-1}) (0.30) (Figure 6).

These results indicate significant phenotypic variability among the progenies for all analyzed traits, supporting the adoption of specific or combined selection

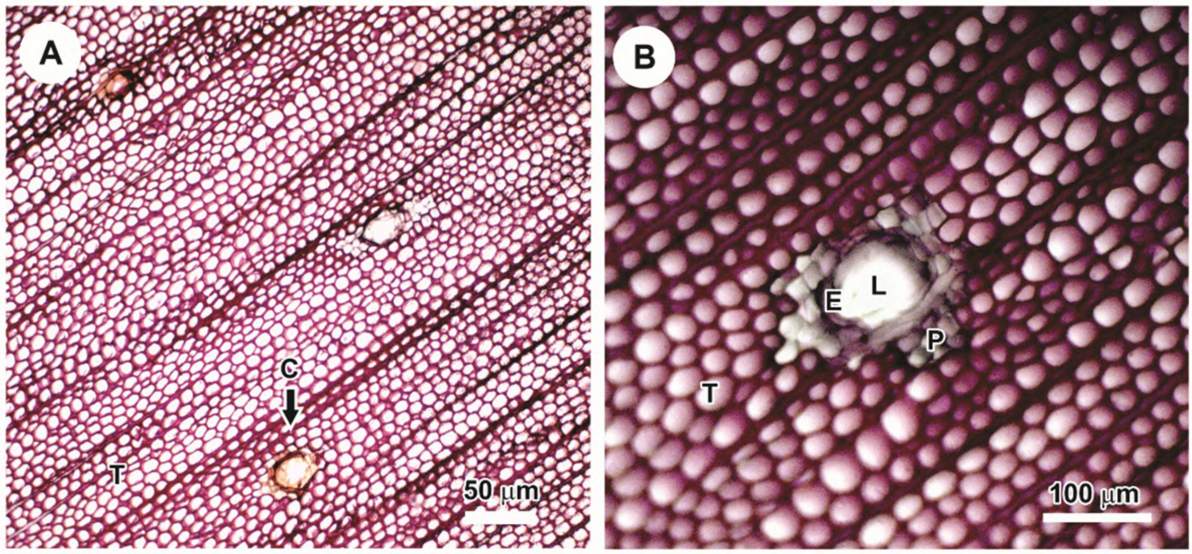

Figure 5. Microscopic structure of the cross-section of *P. caribaea* var. *hondurensis* wood from progenies P63 (A) and P18 (B). C = longitudinal resin canal, T = tracheids, L = lumen, E = epithelial cells, P = parenchyma cells (subsidiaries)

Figura 5. Estrutura microscópica da seção transversal da madeira de *P. caribaea* var. *hondurensis* oriunda das progênies P63 (A) e P18 (B). C = canal resinífero longitudinal, T = traqueídes, L = lúmen, E = células epiteliais, P = células de parênquima (subsidiárias)

strategies, depending on the objectives of the breeding programs, whether focused on growth, gum resin production, or multiple-use purposes.

4. DISCUSSION

ANOVA revealed significant differences among the progenies of *P. caribaea* var. *hondurensis* for all evaluated traits, indicating broad phenotypic variability among the analyzed genetic materials (Bhering et al., 2008; Presotti & Barreto, 2009). Grouping by the Scott-Knott test allowed the discrimination of superior progenies with greater efficiency, especially considering the large number of evaluated treatments, favoring the identification of promising materials for breeding and selection programs (Jelihovschi et al., 2014; Conrado et al., 2017).

Among the evaluated traits, DBH stood out due to its ease of measurement and its potential association with anatomical characteristics (r = 0.74) and productive traits related to gum resin production (r = 0.32), as also reported in other studies (Neis et al., 2019; dos Santos et al., 2016; Yi et al., 2021; López-Alvarez et al., 2023). In this context, high correlations between diameter growth, resin system anatomy, and gum resin production are desirable in genetic trials, as they enable the selection of superior individuals with lower operational effort when compared to direct measurements of gum resin production (Kane & Kolb, 2010).

The moderately high association observed between DBH and NRC (0.74), together with the fact that all progenies with higher NRC were also among those with higher DBH values, suggests that individuals with greater diameter growth tend to exhibit greater development of the resiniferous system. Studies involving *Pinus* species have reported similar behavior, indicating a positive correlation between growth and the number of resin canals (Kane & Kolb, 2010; Ferrenberg et al., 2014; Hood & Sala, 2015; Mason et al., 2019). This pattern may be related to the greater capacity of more vigorous trees to allocate carbon reserves to defense mechanisms, favoring gum resin biosynthesis and the formation of secretory structures (Gaylord et al., 2011).

In this context, vertical and radial resin canals may act as indirect indicators of carbon allocation to defense mechanisms (Hodges et al., 1985; Franceschi et al., 2005), since secondary metabolism in pines is

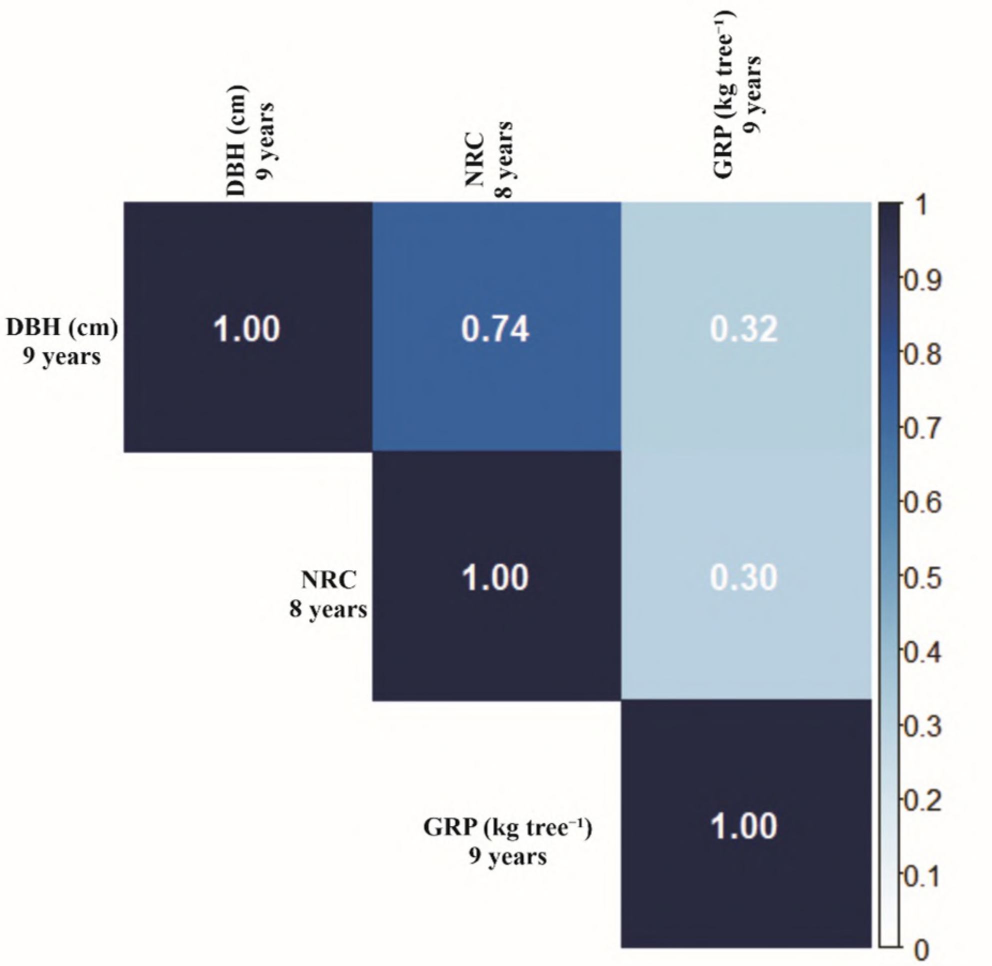

Figure 6. Pearson correlation for DBH (cm), NRC, and GRP (kg tree^{-1}) of *P. caribaea* var. *hondurensis* progenies, in Lavras, MG, Brazil
Figura 6. Correlação de Pearson para DAP (cm), NCR e PGR (kg árvore-^{1}) das progênies de *P. caribaea* var. *hondurensis*, em Lavras - MG

directly related to the availability of remaining carbohydrates (Ruel et al., 1998; Lombardero et al., 2000; Kane & Kolb, 2010). However, the relationship between growth and defense is not linear and may vary under stress conditions, in which physiological trade-offs between these functions may occur (Lorio & Sommers, 1986; Krokene & Nagy, 2012). In addition, contrasting results have also been reported in the literature, as observed by Garcia-Forner et al. (2021), who found greater investment in resin canals in *P. pinaster* trees with lower growth, although under the influence of resin tapping.

In contrast, the low correlation observed between NRC and GRP (0.30), associated with the reduced coincidence among superior progenies for both traits, indicates that a higher density of resin canals does not necessarily imply greater gum resin production. Previous studies have already demonstrated that anatomical characteristics of resin canals do not always exert a direct influence on resin yield in *Pinus* species (Zamski, 1972; Hodges et al., 1981). Similarly, when evaluating *P. elliottii*, Yi et al. (2021) observed that gum resin production did not show a consistent association with resin canal frequency.

Although a positive association trend was observed between DBH and GRP, the low magnitude of the correlation between these variables (0.32) reinforces the multifactorial nature of resin production. Productive efficiency appears to be more associated with tree vigor, expressed by traits such as DBH, crown area, and basal area increment, as well as with the functional capacity for transport and exudation of gum resin through resin canals, rather than with the numerical density of these structures themselves (McDowell et al., 2007; Rodrigues et al., 2008; Garcia-Forner et al., 2021; Neis et al., 2019; Rodríguez-García et al., 2014). Thus, more vigorous trees tend to present greater productive potential, although this response remains conditioned by the interaction among genetic, physiological, environmental, and silvicultural factors (Vázquez-González et al., 2021).

The phenotypic variability identified in the present study indicates potential gains through selection, especially considering that gum resin production is highly dependent on genotype and its interaction with the environment (Li et al., 2022; Tsaktsira et al., 2023). Trees with a greater number and size of stomata, higher nutritional status, and more advanced age tend to produce larger volumes of gum resin, although these characteristics are subject to modulation by factors such as climate, water availability, competition, and extraction techniques (Lema et al., 2024; López-Alvarez et al., 2023).

5. CONCLUSION

The present study revealed broad phenotypic variability among the progenies of *P. caribaea* var. *hondurensis* for diameter growth, number of resin canals, and gum resin production, demonstrating the potential of the evaluated materials for breeding programs focused on resin production in tropical regions. The identification of superior progenies for the different analyzed traits reinforces the possibility of selecting more promising materials based on dendrometric, anatomical, and productive attributes.

The positive association between diameter growth and the number of resin canals indicates that more vigorous trees tend to exhibit greater development of the resiniferous system, highlighting the potential of diameter at breast height as an auxiliary criterion for the selection of superior materials. However, the low association of these variables with gum resin production confirms the multifactorial nature of resin productivity, influenced by the interaction among anatomical, physiological, and environmental factors. Therefore, the results contribute to advancing the understanding of the determinants of gum resin production in *P. caribaea* var. *hondurensis* and provide support for improving selection strategies in breeding programs.

6. ACKNOWLEDGEMENTS

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AUTHOR CONTRIBUTIONS

Oliveira, L.B.: Conceptualization, Data Curation, Investigation, Project Administration, Visualization, Writing – Original Draft, Writing – Review & Editing; Freitas, L.L.J.B.: Data Curation, Investigation, Writing – Original Draft; Bastos, A.O.: Data Curation, Investigation, Writing – Original Draft; Silva Júnior, A.L.: Formal Analysis, Writing – Review & Editing; Mori, F.A.: Conceptualization, Methodology, Validation; Melo, L.A.: Conceptualization, Project Administration, Supervision, Writing – Review & Editing.

DATA AVAILABILITY

The entire dataset supporting the findings of this study has been published within the article.

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