

DOES RESIN TAPPING AFFECT THE TAPERING AND ACCUMULATION OF MERCHANTABLE TIMBER VOLUME IN PINE TREES?

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ABSTRACT

Form factors and taper functions are used for the quantitative and qualitative description of tree stem shape. In southeastern Mexico, there are plantations of *Pinus caribaea* var. *hondurensis* (Sénécl.) W.H. Barrett & Golfari, *Pinus elliottii* var. *elliottii* Engelm., and hybrids between these species to simultaneously produce resin and wood. Farmers need to know whether the practice of resin tapping to death has a negative impact on tree shape and volume of the wood produced. To answer these questions, this study compared the shape, taper, and volume of resin-tapped and untapped trees from three *P. caribaea* origins. A total of 198 trees (99 resin-tapped and 99 untapped) were measured in all diameter categories of the plantation. Total volume models, along with a compatible taper system and variable merchantable timber volume, were fitted using linear and nonlinear regression analyses. To compensate for the lack of initial tree size data prior to tapping, indicator variables (dummies) and an additive structure were used to parameterize volume and taper models. Untapped trees accumulated greater volume than tapped trees. In contrast, the form factor (*ff*) of resin-tapped trees (*ff* = 0.51) was greater than that of untapped trees (*ff* = 0.45). The form factor increased due to tapping between 4 and 7 % depending on the origin, although the hybrid *P. caribaea* × *P. elliottii* presented the most desirable stem geometry in tapped and untapped trees. Based on the Demaerschalk model, the variability is estimated at 99 and 97 % of the merchantable and taper volumes, respectively.

Keywords: *Pinus caribaea* var. *hondurensis*, *Pinus caribaea* × *Pinus elliottii*, shape factor, compatible system, dummy variables, resin.

INTRODUCTION

Pine resin is a valuable non-timber industrial product (Vázquez-González *et al.*, 2021), whose components are used as additives in different food products, pharmaceuticals, agrochemicals, and medicines (Lai *et al.*, 2020). In recent years, its derivatives have

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gained importance to replace fuels and chemicals obtained from petroleum (Neis *et al.*, 2019; Vázquez-González *et al.*, 2021), making resin a renewable natural alternative in the industrial sector. In 2011, plantations of *Pinus caribaea* var. *hondurensis* (Sénécl.) W.H. Barrett & Golfari and *Pinus elliottii* var. *elliottii* Engelm. of different geographical origin were established in Las Choapas, Veracruz, Mexico, to produce resin as part of the Uumbal Agroforestry Project (Torres-Ávila *et al.*, 2020). These species are used in the timber industry and for resin extraction due to their adaptability and the low crystallization rate and high turpentine content of their resin (Lai *et al.*, 2020).

Research on the effect of resin tapping on tree shape and volume accumulation is limited. There has been work analyzing growth patterns through dendrochronological studies on tapped and untapped trees to determine growth in normal diameter, resin accumulation in wood, and tree sensitivity to climatic conditions due to resin tapping (Chen *et al.*, 2015; van der Maaten *et al.*, 2017; Zeng *et al.*, 2021). Recent studies have addressed the impact of resin tapping on wood properties, the partitioning of nonstructural carbohydrates between resin extraction and wood production, and the growth of forest stands subjected to resin tapping to provide a reference for genetic improvement in *P. elliottii* (Du *et al.*, 2022; Wu *et al.*, 2022). Other research has focused on the study of wood mechanical properties in resin-tapped trees, as well as the feasibility of a combined resin-wood production in plantations of *P. caribaea* var. *hondurensis* (Reyes *et al.*, 2015).

The geometry and the stem profile can be evaluated through mathematical models that describe the form factor and taper (Tlaxcala-Méndez *et al.*, 2016). The form factor is described as the ratio between the volume of a tree and that of a cylinder with the same diameter and the same height; knowing this factor makes it easy to calculate the individual volume of the stem. Taper refers to the variation of the stem diameter along its length, which can be estimated using equations that simulate the profile of the tree stem (Hussain *et al.*, 2020).

Given that not all of the trees in Agroforestral Uumbal's plantations are resin-tapped, it is important to understand how the tapped trees are selected. Initially, two reference criteria are established: minimum age of six years and minimum normal diameter of 12 cm. In addition, shape and size play a role, as tapped trees are not considered suitable for high-value timber production (sawmilling). However, tapping can occur before the age of six years if the trees have reached a certain diameter. Tapping can last from 3.5 to 4 years, always trying to leave half of the trees in the stand for timber production only.

The present study initially focused on collecting samples from different sources to construct specific volume models for tapped and untapped trees. This research hypothesizes that stem geometry and shape factor are affected by the resin-tapping that was applied to the trees, and that this in turn modifies the potential accumulation of total volume and product distribution. The objective of this study was to evaluate the potential effect of resin-tapping on the tapering and accumulation of commercial wood volume of trees of *P. caribaea* var. *hondurensis* and the hybrid *P. caribaea* × *P.*

elliottii in commercial plantations in Las Choapas, Veracruz, Mexico, based on the variation in the form factor and its tapering-commercial volume.

MATERIALS AND METHODS

Study area

The study was conducted in commercial forest plantations for resin production in Las Choapas, Veracruz, Mexico ($17^{\circ} 49' 50.59''$ N, $94^{\circ} 6' 11.84''$ W, average altitude of 100 m), belonging to the Uumbal Agroforestry Project. The climate is warm-humid, with year-round, abundant summer rainfalls, annual precipitation of 2400 to 3100 mm, and average minimum and maximum temperatures of 22 and 30 °C (CONABIO, 2001). The physiography includes alluvial plains with hills, flooded coastal alluvial plains, and open valleys with hills. Luvisol and Cambisol soils predominate (INEGI, 2009).

Field data and timber volume estimation

Information was obtained from 198 trees, of which 99 were resin-tapped (*r*) and 99 were untapped (*nr*). Thirty-three trees for each origin group were considered: L1 (*P. caribaea* var. *hondurensis*) from Brazil, L4 (*P. caribaea* var. *hondurensis*) from Australia, and L5 (hybrid *P. caribaea* × *P. elliottii*) from Australia, aged 8, 9, and 8 years, respectively. Trees were resin-tapped on both sides using the American method beginning at six years of age, from stump height (0.1 m) to 2.6 to 3 m high at the stem. The tapping time varied by origin, using 3.5 years for L5 and 4 years for L1 and L4.

The selected trees were felled to obtain accurate diameter data at different stem heights using the stem analysis methodology (Torres-Ávila *et al.*, 2020). A total of 3030 diameter-height pairs of observations were obtained (Figure 1A). The behavior in relative height against relative diameter per stem section of each tree within the

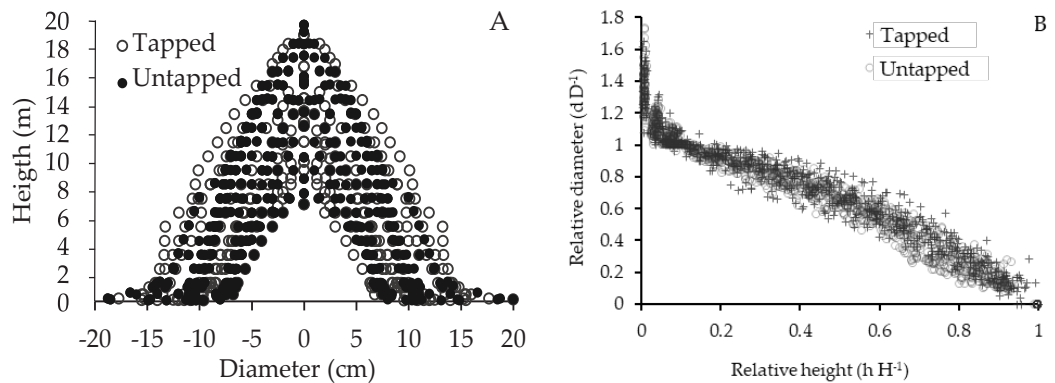


Figure 1. A: Partial heights as a function of partial diameters; B: dispersion of relative heights against relative diameters of the 198 resin-tapped and untapped trees used to adjust the taper and merchantable timber volume functions.

sample followed a logical behavior (Figure 1B). Because no data were available for the trees prior to tapping, the total diameter-height ranges were distributed evenly across origins and tapping conditions.

The Newton formula and the centroid method (Wiant *et al.*, 1992) were used to calculate the volume of the lower and middle sections of the stem, and the cone formula was used for the tip of the tree. This way, the accumulated merchantable timber volume of the sampled trees was obtained (Figure 2A). Total stem volume was calculated using the overlapping log method developed by Bailey (1995) due to its accuracy (Torres-Ávila *et al.*, 2020). The resin-tapped trees were concentrated in categories of 15 to 20 cm of normal diameter, while the untapped trees were grouped in categories of 15 to 35 cm (Figure 2B).

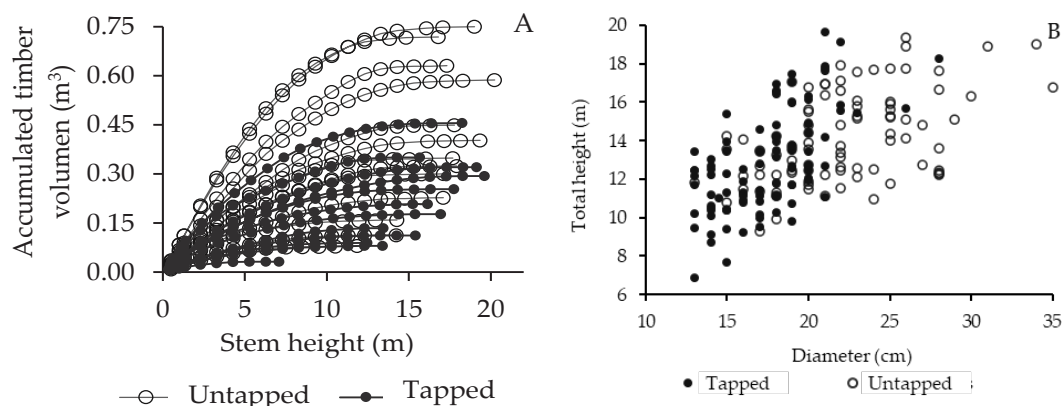


Figure 2. A: Accumulated merchantable timber volume as a function of stem height for the overall sample; B: dispersion of normal diameter-total height observations for the sampled trees.

Effect of resin-tapping and origin on shape and volume factor

Based on the results obtained by Torres-Ávila *et al.* (2020), to estimate the shape factor, a combined variable type total shaft volume model is considered (Bruce and Schumacher, 1942), given by the expression:

$$V = \alpha + \beta \cdot D^2 H$$

where the parameter α (i.e., intercept) is interpreted as the minimum inventoried volume, β is the implicit form factor of the function, D represents the normal diameter (cm), H the total height (m), and V the total timber volume of the stem with bark (m^3). Since $\beta = ff \frac{\pi}{40\,000}$, the form factor compared to the cylinder is $ff = \frac{\beta}{(\pi/40\,000)}$.

Indicator variables (dummies) were used in the statistical analysis to determine if the differences in shape resulting from origin and tapping are statistically significant. These variables have the characteristic of generating categories, taking values of zero or one depending on whether the observation belongs to a certain origin and whether it is resin-tapped (*r*) or not (*nr*). The *nr* trees were taken as the basis for estimating the other parameters in the regression analysis, including the indicator variables in the β parameter as follows:

$$V = \alpha + (\beta_{10} + X_1 \beta_{11}) D^2 H$$

$$\text{where } X_1 = \begin{cases} 1, & \text{if it belongs to a resin tapped tree} \\ 0, & \text{otherwise} \end{cases}$$

The hypothesis test evaluating the tapping effect was $H_0: \beta_{11} = 0$ vs. $H_A: \beta_{11} \neq 0$.

A single regression model was developed considering all trees (*r* and *nr*) of the three origins (L) to test the hypothesis of the shape factor among them. Thus, there were six categories: L1*r* (*P. caribaea* from Brazil, tapped), L1*nr* (*P. caribaea* from Brazil, untapped), L4*r* (*P. caribaea* from Australia, tapped), L4*nr* (*P. caribaea* from Australia, untapped), L5*r* (hybrid from Australia, tapped), and L5*nr* (hybrid from Australia, untapped). To make the parameters estimable, L5*nr* was considered as a reference in the regression analysis. The rest of the parameters are additive to this model, so that the overall function including the indicator variables is defined as:

$$V = \alpha + (\beta_{10} + X_1 \beta_{11} + Z_1 \beta_{20} + Z_1 X_1 \beta_{21} + Z_2 \beta_{30} + Z_2 X_1 \beta_{31}) D^2 H$$

where:

$$Z_1 = \begin{cases} 1, & \text{if it belongs to origin L1} \\ 0, & \text{otherwise} \end{cases}$$

$$Z_2 = \begin{cases} 1, & \text{if it belongs to origin L4} \\ 0, & \text{otherwise} \end{cases}$$

The hypothesis test ($\beta_{10} = 0$) is trivial in this case since there is a general regression function described by α and β_{10} . What is relevant is to identify whether there is significant additionality on the part of the parameters representing the tapping and origin effect. Therefore, the relevant null hypothesis is $H_0: \beta_{11} = \beta_{20} = \beta_{21} = \beta_{30} = \beta_{31} = 0$ vs. H_A : at least one of them is different from zero.

To extend the test, in addition to the suggested constant shape volume model, the Spurr (1952) model, which is of variable shape $V = \alpha_0 (D^2 H)^{\beta_1}$, has goodness of fit, and was fitted nonlinearly (Husch, 1963). To detect changes in total volume between *r* and

nr , the parameters α_0 and b_1 ($\alpha_0 = \alpha_{01} + X_1 \alpha_{02}$ and $\beta_1 = \beta_{11} + X_1 \beta_{12}$) were redefined using the nr as a reference to estimate the other parameters showing the effect of tapping, testing the hypothesis $H_0: \alpha_{02} = \beta_{12} = 0$ against H_A : at least one of them is different from zero.

Evaluation of the effect of resin-tapping and origin on tapering

Initial tests with several taper models identified the Demaerschalk (1972) model, adjusted by Torres-Ávila *et al.* (2020) for data from the plantations and origins studied, as the most efficient due to its goodness of fit. This model is stated as follows:

$$\left(\frac{d}{D}\right)^2 = \theta_0 \left(\frac{1}{D^2 H}\right) X^{\theta_1} + \theta_2 X^{\theta_3},$$

where d is the diameter (cm) with bark of the i -th section at height h (m), D is the normal diameter (cm), H the total height (m), $X = (H - h) / H$, and θ_i represents the parameters to be estimated from the model.

The equations that make up the compatible system of taper total volume and merchantable timber volume generated from integration are as follows (Torres-Ávila *et al.*, 2020):

$$V = k \left(-\frac{\theta_0 \left(\frac{H-h}{H}\right)^{\theta_1+1}}{\theta_1+1} - \frac{\theta_2 D^2 H \left(\frac{H-h}{H}\right)^{\theta_3+1}}{\theta_3+1} \right) \Bigg|_{h_1=0}^{h_2=H} = \frac{k\theta_0}{\theta_1+1} + \frac{k\theta_2}{\theta_3+1} D^2 H$$

$$V_{\text{merchantable}} = k \left(-\frac{\theta_0}{\theta_1+1} \left(\left(\frac{H-h_c}{H}\right)^{\theta_1+1} - \left(\frac{H-h_t}{H}\right)^{\theta_1+1} \right) - \frac{\theta_2 D^2 H}{\theta_3+1} \left(\left(\frac{H-h_c}{H}\right)^{\theta_3+1} \left(\frac{H-h_t}{H}\right)^{\theta_3+1} \right) \right)$$

where k is the constant used when diameters are expressed in cm and lengths in m; h , h_t , and h_c are heights (m) of the i -th section at a certain diameter (cm); h_c is the height (m) above the stump at which the merchantable timber volume is given; and h_t is the height (m) of the stump.

The implied total volume model is of the combined variable type (constant form):

$$V = \frac{k\theta_0}{\theta_1+1} + \frac{k\theta_2}{\theta_3+1} D^2 H$$

To test the hypotheses, the model is rewritten based on the parameters θ_2 and θ_3 , taking the $L5nr$ group as a reference:

$$\theta_2 = \theta_{20} + X_1 \theta_{21} + Z_1 \theta_{22} + X_1 Z_1 \theta_{23} + Z_2 \theta_{24} + X_1 Z_2 \theta_{25}$$

$$\theta_3 = \theta_{30} + X_1 \theta_{31} + Z_1 \theta_{32} + X_1 Z_1 \theta_{33} + Z_2 \theta_{34} + X_1 Z_2 \theta_{35}$$

Analogous to the shape factor and total volume hypothesis tests, the null hypothesis for taper was tested on the parameters indicating the effects of origin and tapping, so $H_0: \theta_{21} = \theta_{22} = \theta_{23} = \theta_{24} = \theta_{25} = \theta_{31} = \theta_{32} = \theta_{33} = \theta_{34} = \theta_{35} = 0$ vs. H_A : at least one of them is different from zero.

Similarly, the parameters θ_0 and θ_1 , which represent the intercept in this taper equation, were tested on whether they are different between tapped and untapped trees, taking the nr trees as the basis for estimating the other parameters in the regression analysis, including the indicator variables in θ_0 and θ_1 :

$$\theta_0 = \theta_{00} + X_1 \theta_{01}$$

$$\theta_1 = \theta_{10} + X_1 \theta_{11}$$

where:

$$X_1 = \begin{cases} 1, & \text{if it belongs to a resin tapped tree} \\ 0, & \text{otherwise} \end{cases}$$

The null hypothesis test evaluating the resin-tapping effect is $H_0: \theta_{01} = \theta_{11} = 0$ vs. $H_A: \theta_{01} \neq \theta_{11} \neq 0$.

Fitting strategy

Parameter estimation of the linear combined variable and total Spurr volume models was performed using the ordinary least squares method with the MODEL procedure of SAS® 9.0 (SAS Institute Inc, 2004), including simultaneous estimation with full information maximum likelihood (FIML) for the compatible system fit of taper-merchantable timber volume. The residuals were analyzed graphically to ensure compliance with homoscedasticity and autocorrelation assumptions in the regression analysis (Ramírez-Martínez *et al.*, 2018).

A power function of the variance of the residual $\sigma_i^2 = (D^2H)^\Phi$ was used to correct for the heteroscedasticity associated with the total and merchantable timber volume. The Φ value was estimated using the method proposed by Harvey (1976), which considers the unweighted errors as the dependent variable in the potential error variance model. The estimation of these functions was performed using the weighted function with the SAS® 9.0 procedure option *resid. VT = resid. VT / ((D²H)^Φ)^{0.5}*.

Autocorrelation was corrected using a second-order continuous autoregressive structure (CAR 2) in the fit of the Demaerschalk taper and taper-merchantable timber volume models. The adjusted coefficient of determination (R^2_{Adj}), sum of squares of error (SCE), and root mean square of error (RMSE) (Torres-Ávila *et al.*, 2020) were used to choose the models with the best goodness of fit.

RESULTS AND DISCUSSION

Effect of resin-tapping on form factor and total tree volume

The Spurr model showed a slightly higher fit than the Bruce and Schumacher model; however, it did not detect an effect of resin-tapping with parameters α_{11} and β_{11} ($p > 0.05$) in contrast to parameter β_{11} ($p < 0.01$) of the Bruce and Schumacher model, which indicates positive additionality due to resin-tapping (Table 1).

Table 1. Total volume models fitted for resin-tapped and untapped pines in forest plantations in Las Choapas, Veracruz, Mexico.

Model	P	Value	EE	t value	Pr > t	SCE	RMSE	R^2_{Adj}
Spurr	α_{10}	7.200E-05	3.092E-06	23.37	<.0001	0.119	0.0173	0.98
	α_{11}	1.300E-05	1.100E-05	1.17	0.2446			
	β_{10}	0.923	5.160E-03	179.10	<.0001			
	β_{11}	-0.011	0.016	-0.70	0.4869			
Bruce and Schumacher	α	2.917E-03	1.770E-04	16.46	<.0001	0.167	0.0206	0.97
	β_{10}	3.700E-05	2.519E-07	148	<.0001			
	β_{11}	3.317E-06	4.373E-07	7.59	<.0001			

P: parameters; EE: standard error; SCE: error sum of squares; RMSE: root mean square error; R^2_{Adj} : adjusted coefficient of determination; α : intercept in common; α_{10} and β_{10} : regression parameters of the reference group (L5nr); α_{11} and β_{11} : parameters of the indicator variables due to tapping.

After detecting the effect of resin-tapping on total volume with the Bruce and Schumacher model, a comparison was made on the form factor for the three origins, including the effect of tapping (Table 2).

For the untapped trees, the reference group origin (L5nr) had the largest form factor. The parameters associated with the effect of resin-tapping always indicate an increase in the form factor compared to the reference trees (L5nr). This effect extends between origins, although for L4, the specific effect of tapping is not statistically significant to the effect of tapping in L5 (Table 2).

Table 2. Results of the linear combined variable model fit with indicator variables to differentiate between origins and resin-tapped and untapped trees.

Group	P	Value	A	ff	EE	t value	Pr > t	SCE	RMSE	R ² _{Adj}
Intercept	α	2.715E-03	2.715E-03	----	1.480E-04	18.35	<.0001			
L5nr	β_{10}	3.900E-05	3.900E-05	0.5	3.649E-07	106.6	<.0001			
L5r	β_{11}	1.908E-06	4.100E-05	0.52	5.847E-07	3.26	0.0012			
L1nr	β_{20}	-1.040E-06	3.800E-05	0.48	5.587E-07	-1.86	0.0631	0.14	0.019	0.98
L1r	β_{21}	2.700E-06	4.300E-05	0.54	9.084E-07	2.97	0.0031			
L4nr	β_{30}	-3.150E-06	3.600E-05	0.46	5.083E-07	-6.19	<.0001			
L4r	β_{31}	1.178E-06	3.900E-05	0.5	8.416E-07	1.4	0.1623			

P: parameters; A: additionality; ff: form factor; EE: standard error; SCE: error sum of squares; RMSE: root mean square error; L1: *Pinus caribaea* from Brazil; L4: *P. caribaea* from Australia; L5: *P. caribaea* × *P. elliottii* from Australia; R²_{Adj}: adjusted coefficient of determination; α : intercept in common; β_{10} : regression parameter of the reference group (L5nr); β_{11} , β_{20} , β_{21} , β_{30} and β_{31} : parameters showing the effect of tapping and origin.

Effect of resin-tapping and origin on the taper-merchantable timber volume system

In the parameters that refer to the intercept θ_0 and θ_1 , additionalities were detected from resin-tapping ($p < 0.01$), so that the values should be considered to differentiate the equations between *r* (tapped) and *nr* (untapped) trees. Likewise, parameters θ_{21-25} and θ_{31-35} ($p < 0.01$) suggest additionalities by origin and by the effect of resin-tapping compared to the reference trees (L5nr) (Table 3).

The behavior of the residuals for taper (Figure 3A) and merchantable timber volume (m³) (Figure 3B) showed compliance with homoscedasticity and error independence. The results of the fitting indicate that there are differences in taper and merchantable timber volume between resin-tapped and untapped treated trees in all groups (Table 3). Therefore, the parameters obtained from the fitting of the compatible system were used to develop specific equations for each origin under study, and the constant form factor was obtained. The resin-tapped trees presented a larger form factor than the untapped trees in the three origins (Table 4).

The form factor for the *nr* trees of L5 origin had a 0.45 value, while for the *r* trees it was 0.51, which represents an increase of 6 % (Table 4). Similarly, increases of 4 and 7 % can be estimated for the L4 and L1 origins.

Assessment of the effect of tree size on tapering and commercial volume

The results obtained from the total volume and taper-merchantable timber volume models suggest that resin-tapping modifies the geometry of the trunk; specifically, it increases the form factor in all three origins. However, it is necessary to incorporate the average tree size into the analysis to make a more effective comparison. This is

Table 3. Results of the fitting with indicator variables in the compatible taper-merchantable timber volume system based on the Demaerschalk model (1972) for pine plantations in Las Choapas, Veracruz, Mexico.

Group	P	Value	EE	t value	Pr > t	SCE	RMSE	R ² _{Adj}	Model
<i>nr</i>	θ_{00}	6630.31	206.70	32.08	<.0001	0.3469	0.0106	0.99	Merchantable timber volume
<i>r</i>	θ_{01}	-2498.86	288.40	-8.67	<.0001				
<i>nr</i>	θ_{10}	40.8910	2.1428	19.08	<.0001				
<i>r</i>	θ_{11}	11.7011	4.7097	2.48	0.0130				
L5 <i>nr</i>	θ_{20}	1.2505	0.0071	175	<.0001				
L5 <i>r</i>	θ_{21}	0.0493	0.0162	3.05	0.0023				
L1 <i>nr</i>	θ_{22}	-0.0724	0.0089	-8.07	<.0001				
L1 <i>r</i>	θ_{23}	0.1152	0.0176	6.56	<.0001				
L4 <i>nr</i>	θ_{24}	-0.1345	0.0071	-18.94	<.0001				
L4 <i>r</i>	θ_{25}	0.0656	0.0162	4.05	<.0001				
L5 <i>nr</i>	θ_{30}	1.7550	0.0154	114.14	<.0001	6284.9	1.4232	0.97	Taper volume
L5 <i>r</i>	θ_{31}	-0.2196	0.0201	-10.91	<.0001				
L1 <i>nr</i>	θ_{32}	-0.2665	0.0223	-11.96	<.0001				
L1 <i>r</i>	θ_{33}	0.2344	0.0283	8.28	<.0001				
L4 <i>nr</i>	θ_{34}	-0.2913	0.0179	-16.25	<.0001				
L4 <i>r</i>	θ_{35}	0.2896	0.0248	11.67	<.0001				

P: parameters; EE: standard error; L1: *Pinus caribaea* from Brazil; L4: *P. caribaea* from Australia; L5: *P. caribaea* × *P. elliottii* from Australia; *nr*: untapped tree; *r*: tapped tree; θ_{00} and θ_{10} : base regression parameters for the intercept of untapped trees; θ_{01} and θ_{11} : parameters indicating additionality due to tapping on the intercept; θ_{20} and θ_{30} : regression parameters of the reference group (L5*nr*); θ_{21} , θ_{22} , θ_{23} , θ_{24} , θ_{25} , θ_{31} , θ_{32} , θ_{33} , θ_{34} , θ_{35} : parameters of the indicator variables due to origin and tapping effects; SCE: error sum of squares; RMSE: root mean square error; R²_{Adj}: adjusted coefficient of determination.

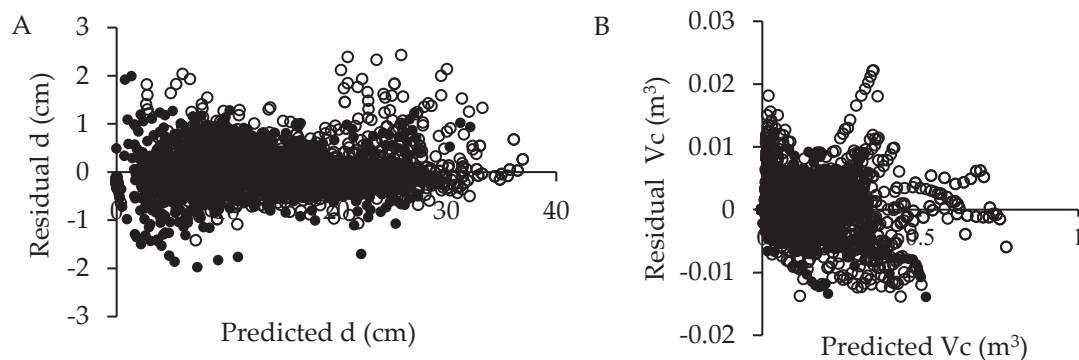


Figure 3. A: Plot of residuals versus predicted taper with diameter (d, cm); B: plot of residuals versus predicted merchantable timber volume (Vc, m³) for the Demaerschalk (1972) model.

Table 4. Estimated parameters for the Demaerschalk (1972) simultaneous taper-merchantable timber volume model and form factor in commercial pine plantations for resin and timber production in Las Choapas, Veracruz, Mexico.

Parameters	Origin	nr	R	ff_{nr}	ff_r
θ_0	L5	6630.3150	4131.4550	0.45	0.51
θ_1		40.8910	52.5922		
θ_2		1.2505	1.2998		
θ_3		1.7550	1.5354		
θ_0	L4	6630.3150	4131.4550	0.45	0.49
θ_1		40.8910	52.5922		
θ_2		1.1159	1.2309		
θ_3		1.4637	1.5338		
θ_0	L1	6630.3150	4131.4550	0.47	0.54
θ_1		40.8910	52.5922		
θ_2		1.1781	1.3427		
θ_3		1.4885	1.5034		

L1: *Pinus caribaea* from Brazil; L4: *P. caribaea* from Australia; L5: *P. caribaea* × *P. elliottii* from Australia; θ_i : parameters of Demaerschalk commercial taper-volume model; nr : untapped trees; r : tapped trees; ff : form factor.

because, in general, resin-tapped trees have smaller diameter and total height than untapped-treated trees.

The company that owns the plantations carries out thinning (i.e., selecting suppressed and intermediate trees); therefore, the accumulated merchantable timber volume is greater in the sample of untapped trees, substantially increasing its value in timber products (Figure 2A). To illustrate the effect of resin-tapping on taper and cumulative merchantable timber volume for each origin, graphs were constructed from the average values of normal diameters and total heights of the sample taken in the plantation (Figure 4), using the specific values of the parameters obtained in the fitting (Table 4). In all origins, the resin-tapped trees showed a tendency to decrease the neiloid shape at the base of the stem and became more like a paraboloid (with relative height from 0 to 0.8), focusing where the tapping began, which ended in a conical shape (relative height from 0.8 to 1). On the other hand, untapped trees presented a neiloid form at the base (0 to 0.2), whose shape is truncated to take a paraboloid shape (0.2 to 0.8) and conical shape at the tip of the tree (0.8 to 1) (Figure 4). In terms of accumulated merchantable timber volume (m^3), the resin-tapped of the three origins accumulated less volume than their untapped counterparts.

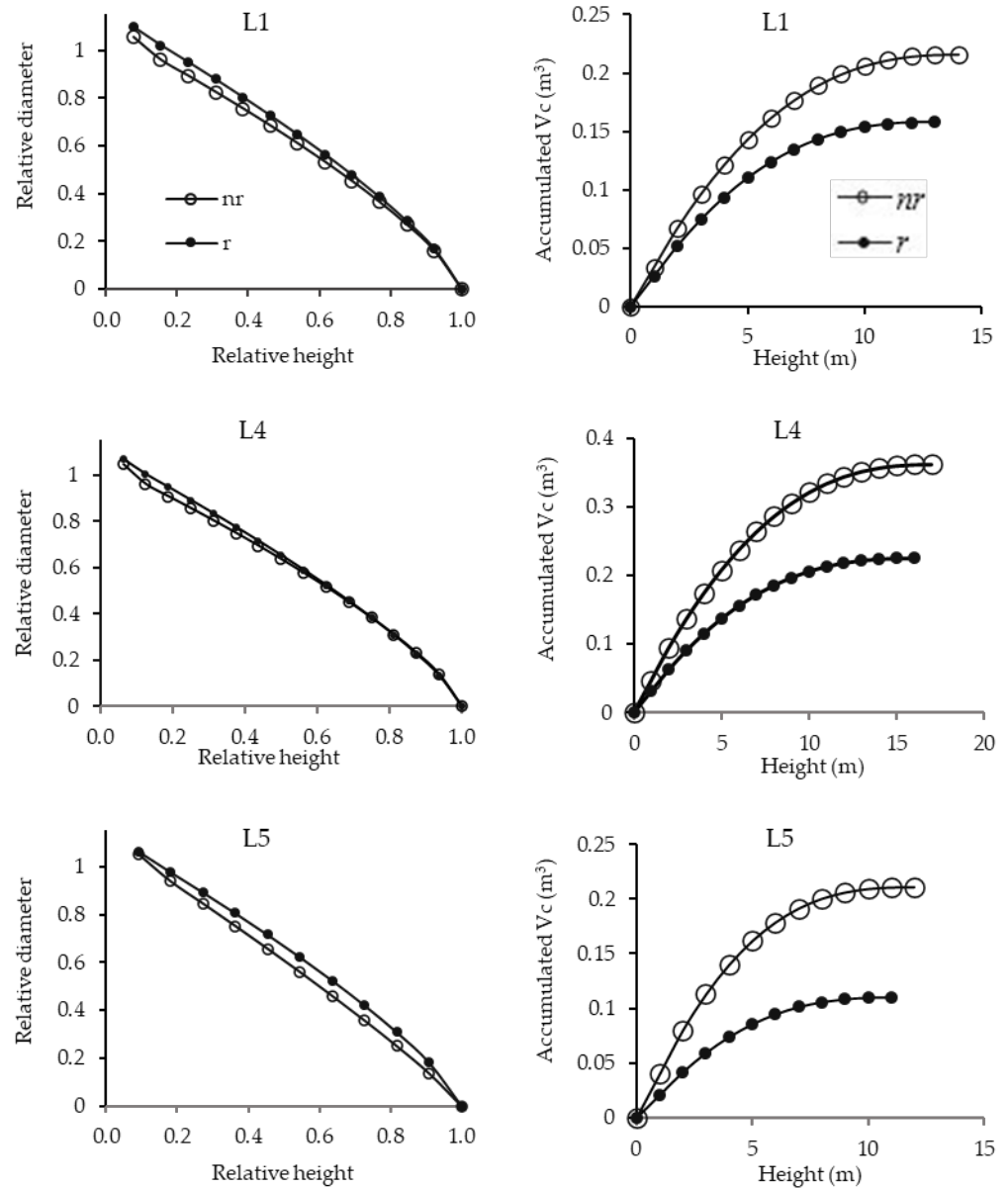


Figure 4. Taper behavior in height and diameter (relative or percentage scale) and cumulative merchantable timber volume (V_c , m^3) in resin-tapped (r) and untapped (nr) trees. L1: *Pinus caribaea* from Brazil; L4: *P. caribaea* from Australia; L5: *P. caribaea* × *P. elliottii* from Australia.

Effect of resin-tapping on the form factor

From the taper-merchantable timber volume models, it is possible to detect differences in the shape and taper factors between resin-tapped and untapped trees and between origins since there are more observations per tree compared to the total volume models, where only one observation per tree is available (Tlaxcala-Méndez *et al.*, 2016). Of the three origins analyzed (Table 4), the hybrid (L5) presented the best behavior in its shape factor, being the least tapered and with a geometry close to the paraboloid. Torres-Ávila *et al.* (2020) mentioned that this behavior can change in situations of water stress in geographical areas where rainy and dry seasons are marked. Better-shaped trees are desirable in the sawmilling industry because more wood processing options can be obtained (Torres-Ávila *et al.*, 2020). Resin-tapped trees presented a significant increase in their form factor compared to untapped trees (Table 4). The form factor is considered an observable characteristic or trait of each origin, affected by the environment in which it develops, its genetic potential, and other management factors. For example, the incidence of borer pests in juvenile stages favors more cylindrical stems (Tlaxcala-Méndez *et al.*, 2016) of Spanish cedar (*Cedrela odorata* L.), as well as resin-tapping in *P. caribaea*, as suggested by the results of this study. Torres-Ávila *et al.* (2020) reported similar values for *nr* trees from these same plantations: 0.48 for L5, 0.44 for L4, and 0.45 for L1. These results indicate that the stem geometry of resin-tapped trees changed in the three origins. For L4, the shape factor is barely close to 0.5, whereas for L1 and L5, this value is higher.

Effect of resin-tapping on taper

Since the stem geometry of the three origins is close to a paraboloid, the Demaerschalk model is the most appropriate to describe it (Torres-Ávila *et al.*, 2020). This model showed that there are differences in the shape and taper factors due to origin and the effect of resin-tapping. Tlaxcala-Méndez *et al.* (2016) mention that this is attributed to the fact that the taper models have more observations per tree, whereas in the total volume models, such as the combined variable and Spurr, there is one observation per tree. Taper models tend to be more sensitive to hypothesis testing. Having more observations allows for more degrees of freedom in the error, and this makes it possible to experiment more successfully with the hypotheses in the taper parameters. The results show that *L4nr*, *L4r*, *L1nr*, *L1r*, and *L5r* express different taper. This is because, when performing the additionality test for the effect of tapping (X) and origin (Z) on the parameters, the effects of the indicator variables X and Z and their interactions are significant. This methodology was used by Tlaxcala-Méndez *et al.* (2016) to find differences in taper, using indicator variables to differentiate between seven geographical origins of *Cedrela odorata* L. in Mexico, where all presented different taper due to genotype-environment interaction and stress caused by borer incidence.

Effect of resin-tapping on wood volume

Studies have been aimed at evaluating the effect of resin production on tree growth, mostly using the dendrochronological approach. However, there are still no studies

on the effect of resin-tapping on tree stem thinning. For example, the effect of resin-tapping on radial growth of *P. massoniana* in southern China showed that growth is greater in tapped trees than untapped trees, with no significant differences (Williams *et al.*, 2017). Du *et al.* (2021) mentioned that the effect of tapping is focused and that grooving had no significant effect on annual radial increment in *P. elliotii*.

Wu *et al.* (2022) found that tapping inhibits stand growth when harvesting is intensive, while Chen *et al.* (2015) indicated that the negative effect on radial growth occurred especially in old trees. On the other hand, van der Maaten *et al.* (2017) showed that in *P. sylvestris*, resin-tapping has a positive effect on tree growth at normal diameter height, suggesting that this is because wood formation is concentrated in the live part of the stem (i.e., after fluting there is no growth on the resin face due to mechanical damage caused to the cambium); however, resin-tapped trees presented slightly higher growth levels 30 years after resin extraction.

In a larger study, conducted from 1967 to 2017 in *P. tubuliformis* in China, tapped trees were shown to have interannual variations consistent with those of untapped trees, although they presented significantly lower values after resin extraction (Zeng *et al.*, 2021). In the present study, it should be considered that the resin-tapped trees are those that are suppressed or co-dominant, which influenced the accumulation of merchantable timber volume, presenting approximately 35 % less accumulated volume at 15 m total height than the untapped trees.

CONCLUSIONS

Resin-tapping did not have a negative effect on the shape factor in trees from the three geographical origins. The best-shaped group is the hybrid (L5), both in tapped and untapped trees, presenting a more cylindrical shape, followed by L1 and L4 being the most tapered. Resin-tapping changed the shape of the stem at the base of the tree, making it resemble a paraboloid. The untapped trees of the three groups accumulated higher merchantable timber volume compared to the tapped ones. This is because the trees selected for tapping correspond to the suppressed and intermediate trees and not to the resin-tapping activity.

The fitted models with indicator variables (dummy) allowed finding differences in the form factor using the taper methodology for resin-tapped and untapped trees of the three origins analyzed. This is because there were more observations per tree in contrast to the total volume models, where there was only one observation per tree. The compatible system of taper and merchantable timber volumes helped improve the sensitivity of the hypothesis tests and find the differences resulting from tapping and origins in the group under study in taper and shape factors.

It is important to emphasize that in order to use the parameters obtained in these analyses, compliance with the assumptions of the regression analysis must be taken into account, and if they are not met, to resort to methodologies that allow improving the behavior of the residuals, such as the autoregressive structure and power functions of the residual variance.

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