DOI: https://doi.org/10.29298/rmcf.v11i60.711

Article

Crecimiento en diámetro, altura, área basal y volumen para tres especies de pino en Chihuahua, México

Diameter, height, basal area and volume growth of three pine species from *Chihuahua*, Mexico

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Resumen

La estimación del crecimiento y rendimiento de las especies forestales maderables es clave para planear y proyectar la cosecha de manera sustentable. El objetivo de la presente investigación fue ajustar cuatro modelos de crecimiento en diámetro, altura, área basal y volumen para *Pinus leiophylla*, *Pinus lumholtzii* y *Pinus strobiformis* de la región de Guadalupe y Calvo, Chihuahua. Mediante un muestreo selectivo se recolectaron 26 árboles de *P. lumholtzii*, 26 de *P. strobiformis* y 30 árboles de *P. leiophylla* para generar 219, 249 y 385 perfiles de cada una de las especies, respectivamente. Los modelos de crecimiento evaluados fueron los de *Chapman-Richards*, *Schumacher*, *Hossfeld I* y *Weibull*. Los criterios de selección de los mejores modelos fueron el coeficiente de determinación, la raíz del error medio cuadrático, ła significancia de los parámetros estimados y las tendencias del crecimiento. Se determinó que todos los modelos presentaron ajustes significativos; sin embargo, por las tendencias del crecimiento que generan, los que mejor representaron el comportamiento biológico de las variables analizadas fueron los de *Chapman-Richards*, *Hossfeld I* y *Schumacher*. Con base en las edades a las que ocurre el máximo incremento en volumen y el turno, se infiere que las tres especies presentan lento crecimiento.

Palabras clave: Altura, crecimiento en área basal, *Pinus leiophylla* Schiede ex Schltdl. & Cham., *Pinus lumholtzii* B.L.Rob. & Fernand, *Pinus strobiformis* Engelm., volumen.

Abstract

The estimation of the growth and the yield of timber forest species is a decisive activity in the sustainable planning and projection of the forest harvest. The purpose of the present study was to adjust four regression models to estimate the diameter, basimetric area, height and volume growth of *Pinus leiophylla*, *Pinus lumholtzii* and *Pinus strobiformis* in *Guadalupe y Calvo*, *Chihuahua,* Mexico. Through selective sampling, 26 *Pinus lumholtzii* trees, 26 *P. strobiformis* trees, and 30 *P. leiophylla* trees were collected in order to generate 219, 249 and 385 profiles, respectively, of each of these species. The adjusted models utilized were those of Chapman-Richards, Schumacher, Hossfeld I and Weibull. The criteria for selecting the best-adjusted models were the coefficient of determination, the root mean square error, the significance of the estimated parameters, and the growth tendency curves. All the models were well adjusted; however, when the growth and yield projection curves were considered, the models that best represented the biological growth trend of the tree species were those of Chapman-Richards, Hossfeld I and Schumacher. Considering the age of maximum growth and the rotation age, the studied species exhibit a low growth.

Key words: Height, basimetric area growth, *Pinus leiophylla* Schiede ex Schltdl. & Cham., *Pinus lumholtzii* B.L.Rob. & Fernand, *Pinus strobiformis* Engelm., volumen growth.

Fecha de recepción/Reception date: 9 de diciembre de 2019
Fecha de aceptación/Acceptance date: 30 de abril de 2020

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Introduction

Sustainable forest management must be supported by information that indicates the current conditions of tree growth and its subsequent development dynamics, in order to guarantee sustained production (Gyawali *et al.*, 2015). This reference is essential to inform and support decision making regarding the management practices to be applied (López and Tamarit, 2005). In order to anticipate the response of the forest to forestry practices and estimate the volume generated over time, it is necessary to generate and apply equations that will allow predicting tree growth based on the age. These require significantly reliable levels of precision (Monárrez and Ramírez, 2003; Quiñonez *et al*., 2015; González *et al.,* 2016) in order to guarantee a good definition of the most appropriate timber volume and age of a tree for commercial exploitation (Valdéz and Lynch, 2000). Within this context, growth estimation is a key factor in planning and predicting sustainable harvesting and implementing better silvicultural alternatives (Salazar *et al.,* 1999; Corral and Návar, 2005), as well as updating forest inventory information (Imaña and Encinas, 2008; Quiñonez *et al.,* 2015).

Depending on the type of forest, regular or irregular to be managed or assess, the study of growth can be approached at the stand level, by diameter classes or by individual trees (Piennar and Rheney, 1995; Gizachew and Brunner 2011). Growth models of individual trees have commonly been generated through stem analyses in order to describe the growth dynamics of timber species that occur in irregular forest areas (Torres and Magaña, 2001). Therefore, in many cases, avoiding periodic remediation facilitates the estimation and analysis of growth dynamics. In turn, the sum of the growth of individual trees results in growth at the stand level (Diéguez *et al.,* 2009).

Studies on the construction of individual tree growth models for species of the genus *Pinus* with commercial timber importance in the state of *Chihuahua* are limited. For this reason, the objective was set to adjust and evaluate models that allow the estimation of growth and increases in diameter, basimetric area, height and volume for *Pinus leiophylla* Schiede ex Schltdl. *P. lumholtzii.* B.L. Rob. & Fernand, *P. strobiformis* Engelm. in the *Guadalupe y Calvo* region, *Chihuahua*.

Materials and Methods

Study area

The study was conducted in the Forest Management Unit 0808 in *Guadalupe y Calvo*, *Chihuahua* (Figure 1), whose area covered by species of the *Pinus* and *Quercus* genera is 642 551 ha (Chávez *et al.*, 2009), located north of the Western *Sierra Madre* and the south of the state of *Chihuahua*, within the R10, the *Sinaloa* Watershed. The predominant climate according to Köppen's classification modified by García (2004) is temperate semi-cold and sub-humid, with a rainy, cool summer C(e)(w_2)(x'). The soils exhibit an albic B subsurface horizon with a medium to thick texture and moderate organic matter content; these soils are classified as Pheozem, Cambisol, Regosol, Litosol, Planosol and Acrisol. The mosaic of temperate plant communities is formed by pure coniferous forests and mixed coniferous and broadleaf forests (Chávez *et al.*, 2009).

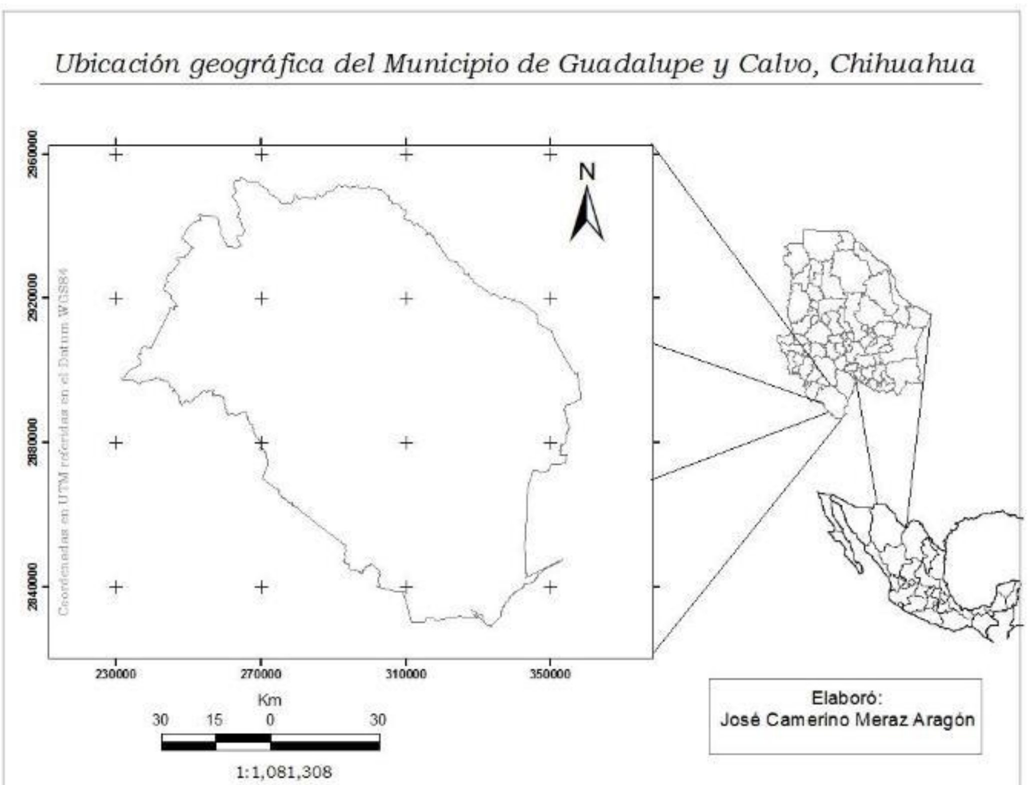


Figure 1. Geographical location of the study area.

Sampling

A sample of 26 *P. lumholtzii* and *P. strobiformis* trees, and 30 *P. leiophylla* trees was collected through targeted sampling in order to include three levels of seasonal quality (low, medium and high); the selected individuals were dominant and co-dominant and exhibited no physical damage. The minimum age for *P. lumholtzii* was 42 years; while those for *P. strobiformis* and *P. leiophylla* were 52 and 75 years, respectively. The selected trees allowed the reconstruction of 219 profiles of *P. lumholtzii*, 249 of *P. strobiformis*, and 385 of *P. leiophylla*, with the stem analysis technique (Klepac, 1983) for estimating the growth and annual increment in diameter, height, basimetric area and volume. Periods of ten years were considered for this purpose.

The reconstruction of the profiles was carried out by measuring and analyzing different diameters and recording the respective ages of the slices, which were obtained from each tree at a height of 0.30 m and 1.30 m from the ground, and then at every 2.60 m, up to the tip of the tree, in order to commercially exploit each of the logs that were extracted.

Variables

The variables of interest were species; normal diameter with bark; diameter without bark of each slice, measured with a Lufkin® rule, starting at the stump; the height of each section, and the number of rings of each slice. The annual growth rings were grouped into 10-year age classes in order to facilitate the estimation of the growth of the normal diameter and the basimetric area. The prediction of the true height per section of the slices was estimated using the formula by Carmean (1972) subsequently modified by Newberry (1991), as expressed in Equation 1.

$$H_{ij} = h_i + \frac{(h_{i+1} - h_i)}{[2(r_i - 0.5)]} + (j-1)\frac{(h_{i+1} - h_i)}{(r_i - 0.5)} \quad (1)$$

Where:

h_{ij} = Estimated slice height of the i^{th} slice, corresponding to growth ring j

h_i = Accumulated height at the top cut of the i^{th} slice

h_{i+1} = Accumulated height up to the upper cut of the previous i^{th} slice

r_i = Number of growth rings of each slice

j = Growth rings from the pith in each slice

The equations for cylinder (2), Smalian (3) and cone (4), respectively, were used to estimate the volume of each section per tree (*i.e.* of the stump, logs and tip of each tree).

$$V_i = \frac{\pi}{4} {D_t}^2 l \quad (2)$$

$$V_i = \frac{\frac{\pi}{4}(D_M^2 + D_m^2)}{2} l \quad (3)$$

$$V_i = \frac{\left(\frac{\pi}{4} {D_b}^2\right) l}{3} \quad (4)$$

Where:

V_i = Log volume

D_t = Upper diameter of the stump

D_M = Largest diameter of each log

D_m = Smallest diameter of each log

D_b = Diameter of the base of the tip (m)

l = Length of the log (m)

Statistical analysis

The quality of the statistical regression adjustment of four growth models was evaluated in order to estimate growth in diameter, basimetric area, height and bark-free volume (Table 1). The respective expressions of these models for the aim of estimating the current annual increment (*CAI*) and the mean annual increment (*MAI*) of individual trees (Kiviste *et al.*, 2001) was also assessed, which are obtained by applying the first derivative to the growth function, and dividing the growth function by the age, respectively.

Table 1. Evaluated growth models and expressions for determining the *CAI* and *MAI*.

Name	Models	*CAI*	*MAI*
Chapman-Richards	$y = a(1-e^{-bt})^c + e$	$CAI = abc(1-e^{-bt})^{c-1}e^{-bt}$	$MAI = \frac{y}{t}$
Hossfeld I	$y = \frac{t^2}{(a+bt)^2} + e$	$CAI = \frac{2at}{(a+bt)^3}$	$MAI = \frac{y}{t}$
Schumacher	$y = ae^{-b\left(\frac{1}{t}\right)} + e$	$CAI = \frac{ab}{t^2}e^{\frac{-b}{t}}$	$MAI = \frac{y}{t}$
Weibull	$y = a\left(1-e^{-bt^c}\right) + e$	$CAI = abct^{c-1}e^{-bt^c}$	$MAI = \frac{y}{t}$

y = Growth in diameter (cm), basimetric area (m^2), height (m) and volume (m^3); *t* = Age (years); *a b* and *c* = Model parameters, *CAI* = Current annual increment in diameter (cm), basimetric area (m^2), height (m), and volume (m^3); *MAI* = Mean annual increment in diameter (cm), basimetric area (m^2), height (m), and volume (m^3).

The adjustment was made by applying the PROC MODEL procedure of the SAS statistical software (SAS, 2002). The goodness of fit of each model was determined by considering the adjusted coefficient of determination ($_{Adj}R^2$), the root mean square error (*RMSE*), and the significance of the parameters for selecting the most efficient model. Also, it was considered the graphic analysis of the growth trend curves, *CAI* and *MAI.*

The observed data of the growth of the analyzed variables kept a serial relationship through time, so that the observations are correlated. This causes the errors of the adjusted regression functions to be correlated as well. Therefore, the significance of this dependence was evaluated for each adjusted model by means of the Durbin-Watson autocorrelation test (*d*) (Sharma *et al*., 2011; Quiñonez *et al*., 2018), which is expressed as follows (5):

$$d = \frac{\sum (e_t - e_{t-1})^2}{\sum e_t^2} \qquad (5)$$

Where:

e_t = Residual *t* of each observation

e_{t-1} = Residual of each observation before the residual e_t

The autocorrelation between the errors of the best models was corrected by applying the auto-regression model CAR(X) developed by Zimmerman *et al.* (2001). This model allows to adjust the parameters of each of the growth models with those of the autoregressive model together. The structure of the autoregressive model is:

$$e_{ij} = \sum \left(d_i \rho_i^{h_{ij} - h_{ij-1}} e_{ij-i}\right) + \epsilon_{ij} \qquad (6)$$

Where:

e_{ij} = The j^{th} ordinary residual in observation i

d_i = 1 for j >1

d_i = 0 for j = 1

$h_{ij} - h_{ij-1}$ and $h_{ij} - h_{ij-2}$ = These are the separation distances between the j^{th} and the j-1^{th} observations and between the j^{th} and the j-2^{th} observations

ϵ_{ij} = Independent error that follows a normal distribution with zero mean and constant variance

After selecting the best model for each analyzed species and variable, the maximum annual increase (CAI_{max}), the maximum annual increase (MAI_{max}) and the point of intersection *CAI*-*MAI* (node) were estimated.

Results

Growth models

Table 2 shows the statistics for the goodness-of-fit of the growth functions evaluated by species. Determination coefficients above 0.95 and standard errors below 2.4 cm for *P. leiophylla* and *P. lumholtzii* indicated a good fit for the four models tested for growth in diameter. For *P. strobiformis*, these same indicators suggested that only Chapman-Richards, Hossfeld I and Schumacher models had a good fit.

Table 2. Statistics of fit of growth models evaluated by variable and by species.

Model	*P. leiophylla*		*P. lumholtzii*		*P. strobiformis*	
	$_{Adj}R^2$	*RMSE*	R^2	*RMSE*	R^2	*RMSE*
Normal diameter						
Chapman-Richards	0.9852	1.2960	0.9594	2.1824	0.9666	1.9555
Hossfeld I	0.9807	1.4805	0.9508	2.4031	0.9628	2.0618
Schumacher	0.9840	1.3463	0.9570	2.2463	0.9643	2.0199
Weibull	0.9850	1.3069	0.9597	2.1742	0.8413	4.2602
Basimetric area						
Chapman-Richards	0.9853	0.0041	0.9696	0.0057	0.9792	0.0051
Hossfeld I	0.9812	0.0046	0.9610	0.0065	0.9734	0.0058
Schumacher	0.9845	0.0042	0.9682	0.0059	0.9787	0.0052
Weibull	0.9848	0.0041	0.9696	0.0057	0.9794	0.0051
Total height						
Chapman-Richards	0.9172	2.0734	0.9422	1.8089	0.9187	1.9792
Hossfeld I	0.9172	2.0710	0.9380	1.8717	0.8209	2.9365
Schumacher	0.9179	2.0613	0.9428	1.7992	0.9167	2.0027
Weibull	0.9167	2.0796	0.9408	1.8308	0.9275	1.8741
Volume						
Chapman-Richards	0.9820	0.0476	0.9766	0.0531	0.9805	0.0601
Hossfeld I	0.9768	0.0539	0.9673	0.0628	0.9739	0.0690
Schumacher	0.9820	0.0475	0.9753	0.0546	0.9809	0.0594
Weibull	0.9818	0.0477	0.9760	0.0538	0.9787	0.0627

In a similar way, the fit of all the models for growth in the basimetric area was good. In general, the R^2 varied between 0.9614 and 0.9854; while the *RSME* ranged between 0.00407 and 0.00651 m^2; the best fits were for *P. leiophylla*, followed by *P. strobiformis* and *P. lumholtzii*.

The fit of the models for estimating the growth in height was also acceptable for all species (0.82223<R^2<0.9433 and 2.9375 m<*RMSE*<1.7992 *m*). The observed difference of the R^2 and RMSE statistics indicated that no model was superior for *P. leiophylla* and *P. lumholtzii*, while the best models for *P. strobiformis* were those of Chapman-Richards, Schumacher and Weibull. The goodness of fit of the models indicated that they all exhibit the best fit in *P. lumholtzii*, followed by *P. leiophylla* and *P. strobiformis*.

Regarding the fit of the models for estimating growth in volume, the statistics R^2 and *RMSE* indicated that all the models exhibited a good fit in each of the species (0.9676< R^2<0.9821 and 0.0475< *RMSE*<0.0690), which suggests that any of them can be applied.

Table 3 shows the values of the estimators for each of the parameters of the models evaluated and selected for growth in diameter, basimetric area, total height and volume, as well as the standard error (*SE*) associated with each of them.

Table 3. Estimators and standard error of growth model parameters in diameter, basimetric area, height and volume by species.

Var	Sp	Model	Parameter and standard error					
			a	***SE***	***B***	***SE***	***c***	***SE***
D	*P. le*	M1	35.2754	1.0392	0.02487	0.0017	4.0365	0.3685
		M2	10.6226	0.4634	0.1079	0.0036		
		M3	56.7817	1.7595	87.8365	3.1368		
	P. lu	M1	36.2857	1.7320	0.0364	0.0039	4.2240	0.6091

		M2	6.3774	0.4640	0.1139	0.0056		
		M3	60.6040	2.9927	63.5601	3.3490		
		M1	37.3437	2.3223	0.0267	0.0032	3.2782	0.3989
	P. st	M2	8.8415	0.5269	0.1015	0.0057		
		M3	58.7729	3.0045	71.5771	3.0708		
		M1	0.0953	0.0047	0.0236	0.0019	7.2289	0.9384
	P. le	M2	360.6967	20.1078	1.4092	0.1344		
		M3	0.2228	0.0123	167.4279	6.7774		
		M1	0.1048	0.0081	0.0346	0.0041	8.0210	1.5057
AB	*P. lu*	M2	274.1521	22.8557	1.0242	0.2128		
		M3	0.2695	0.0248	126.0044	7.8757		
		M1	0.0942	0.0088	0.0285	0.0034	6.7282	1.0969
	P. st	M2	365.2532	29.0127	0.7814	0.2275		
		M3	0.2273	0.0208	134.6815	8.1525		
		M1	22.2187	1.4817	0.0167	0.0031	1.7248	0.2734
	P. le	M2	8.7840	0.6838	0.1698	0.0063		
		M3	28.2632	1.2812	60.3691	3.9339		
		M4	22.1510	1.7086	0.0060	0.0013	1.1329	0.1259
		M1	21.7975	1.1381	0.03425	0.0044	3.1616	0.4970
H	*P. lu*	M2	7.6159	0.5993	0.1483	0.0066		
		M3	33.7714	1.6191	54.1693	3.0924		
		M4	20.6293	0.9681	0.0005	0.0002	1.9043	0.1451
		M1	21.8326	2.1485	0.0186	0.0047	1.5102	0.2703
	P. st	M2	7.0481	0.4862	0.1736	0.0066		
		M3	26.5185	1.3526	46.6345	3.2564		

		M4	22.4653	2.7619	0.0037	0.0017	1.2826	0.1314
		M1	0.9928	0.0930	0.01757	0.0023	5.6134	0.9373
	P. le	M2	163.3303	11.4685	0.23562	0.0678		
		M3	1.9126	0.1334	168.1143	8.2019		
		M1	1.0261	0.0860	0.03497	0.0035	9.4204	1.4908
V	*P. lu*	M2	109.9372	9.4145	0.16841	0.0825		
		M3	3.1270	0.3217	146.3211	8.9529		
		M1	0.6804	0.0661	0.03502	0.0039	6.7662	0.9915
	P. st	M2	122.3973	12.1693	0.21111	0.0975		
		M3	1.6990	0.1525	115.3624	6.5714		

Var = Response variable; *D* = Normal diameter; *AB* = Basimetric area; *H* = Height, *V* = Volume; *P. le = Pinus leiophylla*; *P. lu = Pinus lumholtzii*; *P. st = Pinus strobiformis*; M1 = Chapman-Richards model; M2 = Hossfeld I model; M3 = Schumacher model; M4 = Weibull model; *a*, *b* and *c* = Parameter estimators; *SE* = Standard error of parameter estimators.

The parameter estimators of the growth models in diameter, basimetric area, height and volume of Chapman-Richards, Hossfeld I and Schumacher were significantly different from zero (Pr<0.0001) in all three species studied. In the case of the Weibull height growth model, the parameters were significantly different only for *P. leiophylla* and *P. strobiformis*; in *P. lumholtzii* they were significant only in the asymptote parameters *a* and *c*. Based on the values of R^2 and *RMSE* for selecting the best model of growth in normal diameter, basimetric area, total height and volume, all models showed good fits in each of the assessed species; however, when considering the significance of the parameters, the Weibull model was discarded.

As a complement to the analysis of the results, the trends in the growth curves of the three previously selected models allowed us to determine that those of Schumacher and Chapman-Richards best represented biological growth in normal diameter, basimetric area and volume of *P. leiophylla*; while those of Hossfeld I and Chapman-Richards corresponded to the best trends in height growth. Schumacher's model best characterized the growth in normal diameter, basimetric area, height and volume of both *P. lumholtzii* and *P. strobiformis*. In the latter species, the Chapman-Richards model also exhibited a good trend in height growth (figures 2, 3 and 4).

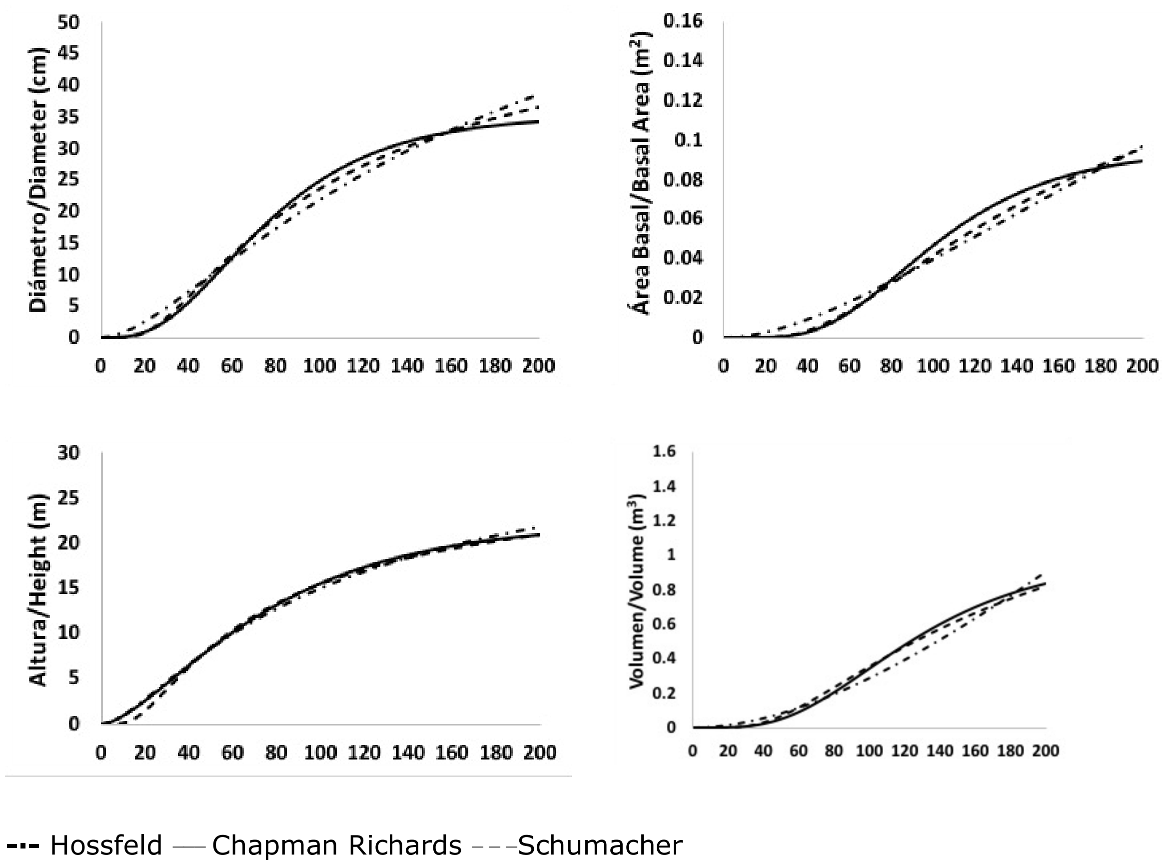


Figure 2. Trends in the average growth of normal diameter, basimetric area, height and volume of the Chapman-Richards, Hossfeld I and Schumacher models of *Pinus leiophylla* Schiede ex Schltdl. & Cham.

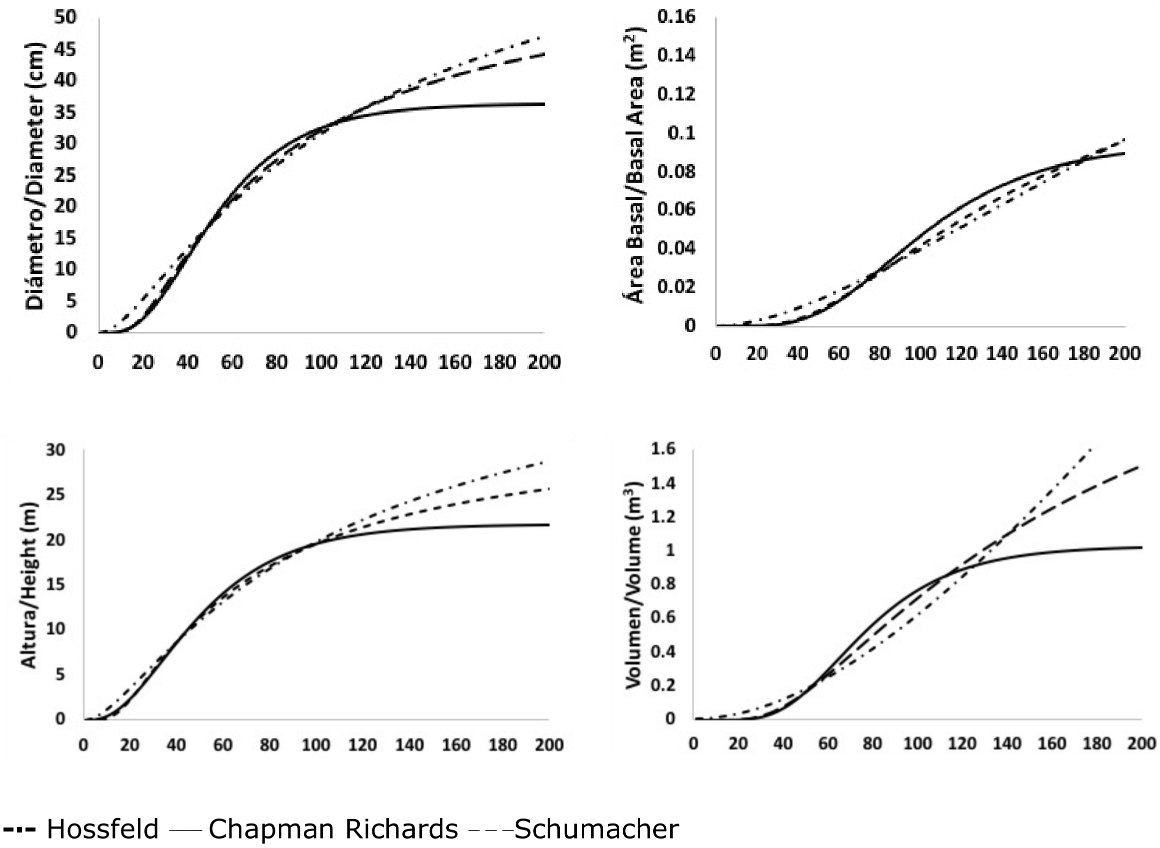
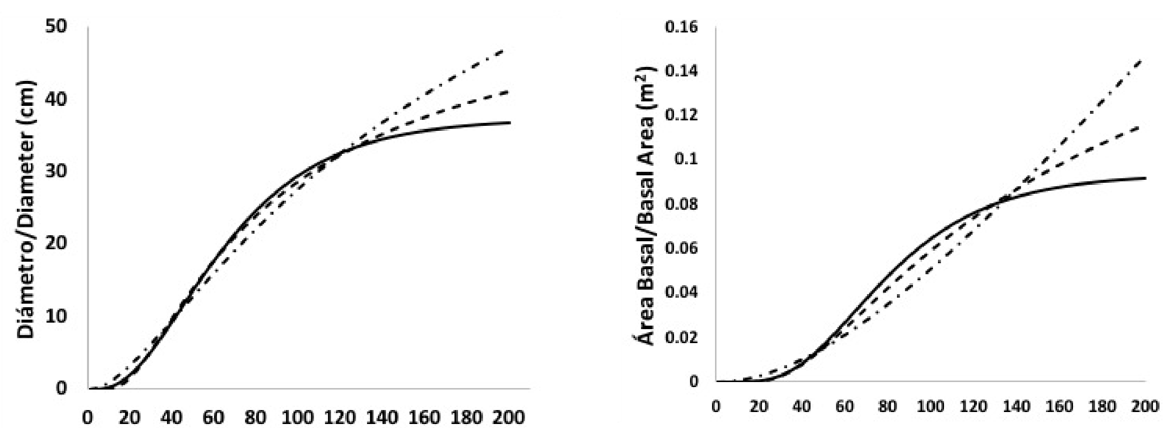
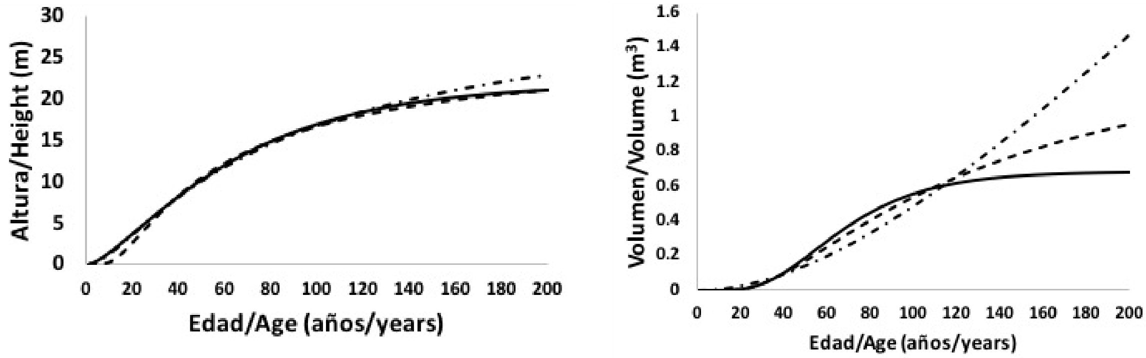


Figure 3. Trends in the average growth of normal diameter, basimetric area, height and volume of the Chapman-Richards, Hossfeld I and Schumacher models of *Pinus lumholtzii* B.L.Rob. & Fernand.





-·- Hossfeld —— Chapman Richards – – –Schumacher

Figure 4. Trends in the average growth of normal diameter, basimetric area, height and volume of the Chapman-Richards, Hossfeld I and Schumacher models of *Pinus strobiformis* Engelm.

Current and average annual increment

Pinus lumholtzii was the species that exhibited the highest CAI_{max} in each one of the studied variables, followed by *P. strobiformis* and *P. leiophylla*. In *P. lumholtzii*, the CAI_{max} in diameter was presented at the age (*t*) of 30 years, much earlier than in *P. leiophylla* (*t=55*) and *P. strobiformis* (*t=35*). The age at which the CAI_{max} was recorded in the basimetric area of *P. leiophylla* was higher (*t=85 years*) than that calculated for *P. lumholtzii* (*E=25 years*) and *P. strobiformis* (*t*=25 years) (Table 4).

Table 4. Maximum annual incremental current (CAI_{max}) and annual mean increment (MAI_{max}) estimated for each of the variables by species.

Variable	**Species**	**Model**	**CAI_{max}**	**Age of the CAI_{max} (years)**	**MAI_{max}**	**CAI-MAI Intersection (years)**
Diameter (cm)	*P. le*	M1	0.369	55	0.249	95
		M3	0.349	45	0.238	90
	P. lu	M3	0.514	30	0.351	65
	P. st	M3	0.444	35	0.302	75
Basimetric area (m^2)	*P. le*	M1	0.00089	85	0.00049	170
		M3	0.00072	85	0.00049	135
	P. lu	M3	0.00116	65	0.00078	125
	P. st	M3	0.00091	65	0.00062	135
Height (m)	*P. le*	M1	0.1978	35	0.16841	60
		M2	0.1985	25	0.16751	50
	P. lu	M3	0.3352	25	0.22932	55
	P. st	M1	0.2327	25	0.20636	40
		M3	0.3063	25	0.20905	45
Volume (m^3)	*P. le*	M1	0.00705	100	0.00438	160
		M3	0.00616	85	0.00418	170
	P. lu	M3	0.01156	75	0.00786	145
	P. st	M3	0.00796	60	0.00541	115

P. le = *Pinus leiophylla*; *P. lu* = *Pinus lumholtzii*; *P. st* = *Pinus strobiformis*; M1 = Chapman-Richards model; M2 = Hossfeld I model; M3 = Schumacher model; CAI_{max} = Maximum current annual increase; MAI_{max} = Maximum mean annual increase.

The age at which the CAI_{max} in height was estimated with the Hossfeld, Schumacher and Chapman-Richards models in the three species was 25 years, while the estimated age for the CAI_{max} in volume was highest in *P. leiophylla*, followed by *P. lumholtzii* and *P. strobiformis*. Considering that the optimal age for defining the physical rotation of forest species happens when the *CAI* and the *MAI* in volume are equal (Mendoza, 1983), the rotation age for *P. leiophylla* estimated with Schumacher's equation was 170 years, in *P. lumholtzii* 145 years and in *P. strobiformis* 115 years.

Discussion

Growth models

Similar studies have documented that the Chapman-Richards and Schumacher models are well suited for estimating the growth of individual trees. For example, Arteaga (2000) evaluated several height growth models for estimating the site index for *P. radiata* D. Don, *P. oaxacana* Mirov and *P. pseudostrobus* Lindl., and Monárrez and Ramírez (2003) for *P. durangensis* Martínez reported that Chapman-Richards' model had the best fit.

Likewise, Corral and Návar (2005) indicated that this model is the best for estimating growth and increase in diameter, basimetric area, height and volume in five pine species in the state of *Durango*; while Quiñonez *et al.* (2015) record that this same model, in the form of algebraic differential equations, is the best for estimating growth in normal diameter of *P. lumholtzii*. Hernández *et al.* (2014), when adjusting various regression models to estimate growth in height and determine the site index for *P. gregii* Engelm. ex Parl., point to Schumacher's model as the one that presented the best fit; this model also exhibited a good fit for estimating the growth in normal diameter in *P. durangensis* (Monárrez and Ramírez, 2003).

Current and mean annual increase

Based on the estimations of the CAI_{max}, MAI_{max}, the age at which the maximum annual current increase and the physical shift of each variable are attained, we infer that the species analyzed herein achieve lower CAI_{max} or require more time than other species of the same genus to reach the maximum increases and rotation age. As evidence of the above, we cite the CAI_{max} for normal diameter (0.75 cm), basimetric area (0.009 m^2), height (0.74 m) and volume (0.048 m^3) in *P. herrerae* Martínez (Calvillo *et al.*, 2005); and for height in *P. cooperi* C.E.Blanco (0.39 m), *P. durangensis* (0.35 m), *P. engelmanii* Carr. (0.40 m, *P. herrerae* (0.43 m) (Corral and Návar, 2005) were superior to *P. leiophylla*, *P. lumholtzii* and *P. strobiformis*, species evaluated in this study.

When comparing the CAI_{max} registered by Corral and Návar (2005) for *P. leiophylla* with those observed in the present research, we conclude that the CAI_{max} in height (0.32 m *vs* 0.197 m) and volume were higher (0.008 m^3 *vs* 0.007 m^3), while that of the diameter (0.32 m) was lower (0.32 cm *vs* 0.35 cm).

When considering the age at which CAI_{max} occurs in order to evaluate the growth of *P. cooperi*, *P. durangensis*, *P. engelmanii*, *P. herrerae* and *P. leiophylla* in the state of *Durango*, Corral and Návar (2005) determined that CAI_{max} in diameter occurred between one and 16 years, and in height, between 19 and 24 years —ages lower than those estimated for those variables in the three species evaluated in this study. However, the age at which the CAI_{max} occurred in volume (70 to 105 years) was similar to that estimated by Corral and Návar (2005) for *P. leiophylla*, *P. lumholtzii* and *P. strobiformis* (100, 75 and 60 years, respectively).

The *CAI-MAI* intersection of the volume estimated by Corral and Návar (2005) for *P. leiophylla* is lower than that documented herein for the same species (155 years *vs* 160-170 years). Monárrez and Ramírez (2003) indicate that the ages at which CAI_{max} and the physical rotation age in the diameter (*t=17 years* and *t=35 years*) and height (*t=15 years* and *t=28 years*) of *P. durangensis* occur were also lower than those determined for the species assessed in this study. Quiñonez *et al.* (2015)

report that among six *Pinus* species, *P. lumholtzii* and *P. leiophylla* show the slowest growth in normal diameter and basimetric area; the authors argue that the slow growth that characterizes these two taxa explains the lack of interest in exploiting them economically.

Conclusions

Chapman-Richards' and Schumacher's models have the best fit for predicting growth in normal diameter, basimetric area and volume in *P. leiophylla*, while the Hossfeld I and Chapman-Richards models are the best fit to predict the growth in height. On the other hand, Schumacher's model is best suited to predict growth in normal diameter, basimetric area, total height and volume in *P. lumholtzii* and *P. strobiformis*. The ages of the physical volume rotation age for *P. leiophylla*, *P. lumholtzii* and *P. strobiformis* correspond to 170, 145 and 115 years, respectively. Within the study area, these species exhibit a slow growth. The growth equations currently applied in the region of Forest Management Unit 0808 *Guadalupe y Calvo, Chihuahua*, should be compared with those proposed in this study in order to validate and assess their practical application.

Conflict of interests

The authors declare no conflict of interests with any institution.

Contribution by author

Francisco Javier Hernández: organization, validation and analysis of the information, and drafting of the manuscript; José Camerino Meraz Aragón: organization, validation and analysis of the information; Benedicto Vargas Larreta: analysis of the information and editing of the manuscript; Juan Abel Nájera Luna: analysis of the information, and drafting and editing of the manuscript.

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