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Article

Crecimiento e incremento en biomasa y carbono de *Pinus teocote* Schltdl. *et* Cham. y *Pinus oocarpa* Schiede., Guerrero, México

Biomass and carbon growth and increases of *Pinus teocote* Schltdl. *et* Cham*. and Pinus oocarpa* Schiede., state of *Guerrero*, Mexico

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Resumen

La modelización del crecimiento en biomasa es una de las técnicas más importantes para conocer el *stock* de carbono en cualquier intervalo de desarrollo en una planta, y permite tomar decisiones de manejo forestal para fines de mitigación del cambio climático. El objetivo de este estudio fue ajustar modelos de crecimiento para cuantificar incrementos en biomasa (*B*) y captura de carbono (*C*) en bosques maduros de *Pinus teocote* y *Pinus oocarpa*, en la región de la montaña del estado de Guerrero. Se derribaron 24 árboles por especie, y mediante la técnica de análisis troncales se ajustaron cinco modelos de crecimiento, posteriormente se determinaron los puntos de inflexión del incremento corriente anual (ICA), incremento medio anual (IMA) y el turno técnico. El modelo de *Weibull* presentó los mejores ajustes para determinar el crecimiento en biomasa aérea (*B*); la ecuación resultante en *P. teocote* fue $Y = 1722.1(1\text{-}e^{-3.933E\text{-}6*X^{2.7928}})$, R^2adj = 0.73, *REMC* = 184.2 kg y $\overline{e}$ = 125 kg. En *P. oocarpa* la ecuación de crecimiento fue $Y = 3186.79(1\text{-}e^{-0.000033*X^{2.2103}})$, R^2adj = 0.88 *REMC* = 155.9 y $\overline{e}$ =108.2 kg. El análisis del crecimiento proyectado hasta el turno técnico en *B* (107 y 126 años) produciría incrementos de 2.81 t ha^{-1} año^{-1} de *B* en *P. teocote* y 3.64 t ha^{-1} en *Pinus oocarpa*. Los modelos de crecimiento son confiables y eficientes para estimar biomasa e inferir la captura de carbono con base en la técnica de análisis troncal en bosques maduros de *P. teocote* y *P. oocarpa* en la región estudiada.

Palabras clave: Análisis troncales, anillos de crecimiento, bosque maduro, modelización, *Pinus oocarpa* Schiede., *Pinus teocote* Schltdl. *et* Cham.

Abstract

The modeling of growth in biomass can be one of the most important techniques for determining the carbon stock in any interval of development in the plant, allowing to make decisions about the management of the species for climate change mitigation. The goal of this study was to adjust growth models to quantify biomass increments *(B)* and estimate the carbon uptake *(C)* in *Pinus teocote* and *Pinus oocarpa* forests in the mountain region of the state of *Guerrero.* Twenty-four trees per species were felled, tree trunk analyses were performed, and five growth models were adjusted in order to estimate the increments in biomass and the inflection points of the current annual increase (CAI), mean annual increase (MAI), and the technical shift where CAI and MAI intersect. Weibull's model exhibited the best adjustments for determining biomass growths; the equation for estimating biomass in *P. teocote* was: $Y = 1722.1(1\text{-}e^{-3.933E\text{-}6*X^{2.7928}})$, R^2adj 0.73, *REMC* = 184.2 kg and $\overline{e}$ = 125 kg; the generated model for *P. oocarpa* was $Y = 3186.79(1\text{-}e^{-0.000033*X^{2.2103}})$, $adjR^2$ = 0.88 *RMSE* = 155.9 and $\overline{e}$ = 108.2 kg. The analysis of the projected growth until the technical shift (107 and 126 years) yielded increments of 2.81 t of *B* ha^{-1} year^{-1} in *P. teocote* and 3.64 t ha^{-1} year^{-1} in *P. oocarpa*. The growth models are reliable and efficient for estimating biomass and inferring carbon uptake based on the application of the ring analysis technique in mature *P. oocarpa* and *P. teocote* forests in the studied region.

Keywords: Trunk analysis, growth rings, mature forest, modeling, *Pinus oocarpa* Schiede., *Pinus teocote* Schltdl. *et* Cham.

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Introduction

Forests are important carbon sinks for the planet, helping to mitigate climate change caused mainly by high concentrations of carbon dioxide (CO_2) in the atmosphere (Ordóñez *et al.,* 2015; Palacios-Cruz *et al.,* 2020).

Generally, forests that grow faster in juvenile stages and have net growth are able to capture more carbon dioxide (CO_2) than they emit through respiration, until this process gradually stabilizes in mature stages (Orihuela-Belmonte *et al.,* 2013; Casiano *et al.,* 2018); these include fast-growing plantations (Téllez *et al.,* 2019; Jiménez *et al.,* 2020).

However, rapid plant growth in early stages may also be the result of the presence of anthropogenic factors such as forest fires or land use changes involving secondary successions in the ecosystem (Aryal *et al.,* 2014). It has even been documented that forest management activities through silvicultural practices have a positive impact on carbon sequestration and storage, due to the type of forest and management conditions (Monárrez *et al.,* 2018; Palacios-Cruz *et al.,* 2020).

Growth modeling is the most powerful management tool for decision making, as it allows to determine the most appropriate strategies for the use and conservation of forest resources, both in the present and in the future (Salas *et al.,* 2016; Santiago *et al.,* 2020). It is also vital to know the productivity of ecosystems, determine growth and increment, and define forestry shifts and the use of a species according to the time and quality of the site (Aguirre, 2015).

Biomass modeling for carbon estimation, in particular, is a reliable tool for measuring the storage capacity of trees as a climate change mitigation strategy and is also an important aspect to consider in carbon inventory planning (Fonseca *et al.,* 2021), contributing to the development of sustainable management practices and species conservation strategies, in which timber production is not the main function (Cuevas and Aquino, 2020).

In recent years, about 90 research papers related to carbon estimation from chronosequences have been cited (Casiano *et al.,* 2018), of which 8 % are related to carbon sequestration through the analysis and modeling of growth rings (Reyes *et al.,* 2020); most of these studies have focused on young forest plantations (Pompa and Sigala, 2017).

Therefore, in the present research the goodness of fit of five growth models to efficiently estimate biomass stock and carbon sequestration through growth rings for individual trees in mature *Pinus teocote* Schltdl. *et* Cham. and *Pinus oocarpa* Schiede. forests of the mountainous region of the state of Guerrero, Mexico was tested. The null hypothesis (H_0) stated in this research is that there are no differences in carbon uptake between the two species studied.

Materials and Methods

Study area

The study area is located between 17°01'45" and 17°15'30" N, and 98°39'24" W (Figure 1), at an altitude of 1 800 to 2 100 m (Figure 2) (INEGI, 2014). It includes *Iliatenco* and *Malinaltepec* municipalities in the mountain region of the state of *Guerrero*, Mexico. The predominant vegetation is pine-oak forests, where *P. teocote* and *P. oocarpa* grow naturally in pure stands.

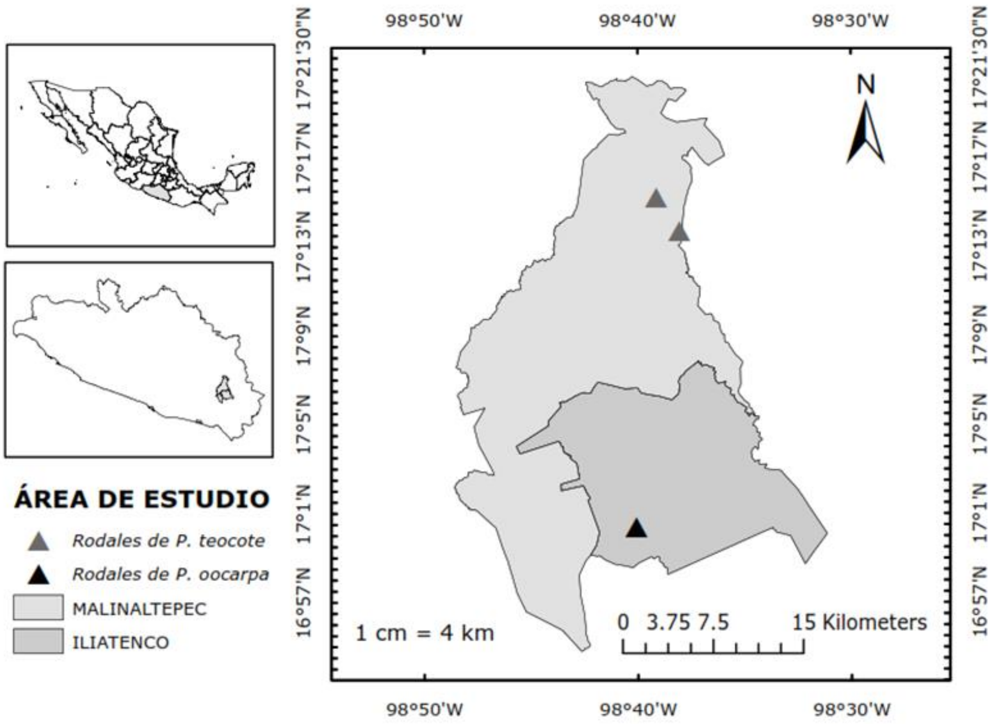


Figure 1. Geographic location of the study area.

The zone has a A(c) w_2 (2) climate, which corresponds to semi-warm temperate, with intense rainfall in the months of July-August; the minimum and maximum temperatures vary from -3 to 26 °C, respectively. The soil type is mostly Regosol, with abundant organic matter (INEGI, 2008; INEGI, 2014).

Database

Twenty four dominant trees per species were felled from mature unispecific stands representing all diameter categories (5-60 cm) (Marroquín *et al.,* 2018; Martínez *et al.,* 2019), selected in 20 circular sites of 500 m^2 and randomly distributed in each stand (Ancira-Sánchez and Treviño, 2015). The number of individuals per site was then obtained and extrapolated to individuals per hectare (ind ha^{-1}): 210 ind ha^{-1} for *P. teocote,* and 190 ha^{-1} for *P. oocarpa*.

Forest profiles were constructed by measuring and analyzing different diameters and recording the respective ages of the slices according to the log analysis technique (Klepac, 1976); the slices were obtained from each tree at the heights of 0.30 m, 1.30 m, and subsequently every 2 m, until reaching the tip (Hernández *et al.,* 2020). The slices were prepared with a DWE6411 DeWalt orbital sander and LT-0100 SAYER clear varnish for high gloss wood (Pineda *et al.,* 2015) to facilitate direct reading of annual rings using the conventional method (González *et al.,* 2016).

Variables analysis

Unbarked diameters were measured with a 50 cm Arly 3003 ruler on the 5 and 10 year rings of each slice along the entire length of the stem (Reyes *et al.,* 2019); the basimetric area (*G*) in m^2 was then determined; the volume (m^3) per section *i* was estimated using the individual summation by dendrometric type (Uranga *et al.,* 2015) —stump, logs and tips—, based on the formula of the cylinder (1), Smalian (2), and cone (3), in order of mention:

$$StV = G * L \qquad (1)$$

$$LV = \frac{G_1 + G_2}{2} * L \qquad (2)$$

$$Vc = \frac{G_3}{3} * L \qquad (3)$$

Where:

StV = Stump volume

G = Basimetric area in m^2 of the stump section

LV = Log volume (m^3)

G_1 = Basimetric (m^2) of the largest section of the log

G_2 = Basimetric (m^2) of the smallest section of the log

G_3 = Basimetric (m^2) of the tip section

L= Length of the section (m)

The biomass per section was determined with the indirect method (Brown *et al.,* 1989; Chave *et al.,* 2005; Fonseca, 2017), which uses the values of the forest volume per section and the average basic density (*BD*) according to the following equation (4); *the BD* was 450 kg m^{-3} for *P. teocote*, and 500 kg m^{-3} for *P. oocarpa* (Ríos, 2021).

$$Sb = BD*SV \qquad (4)$$

Where:

Sb = Stem biomass (kg) per age section i

BD = Basic density (kg m^{-3})

SV = Stem volume per age section i

The aboveground biomass (B) of each section of age i was obtained with the expression (5), which adds the average percentage (%) of leaf-branch biomass (Bhr) previously determined by Ríos (2021), of 24.6 % in *P. oocarpa* and 29.6 % in *P. teocote*.

$$B = SB + SB * \left(\frac{L\text{-}BB}{100}\right) \qquad (5)$$

Where:

B = Aboveground biomass (kg) per age section i

SB = Stem biomass (kg)

$L\text{-}BB$ = Leaf-branch biomass (kg)

The Carbon (*C*) fixed in the *B* of each species at age *i*, was calculated as the product of *B* times the percentage of *C* quoted by Yerena *et al.* (2012) for *P. teocote* (47 %); the percentage used for *P. oocarpa* was 48 % —a conservative figure compared to the one estimated by the IPCC (2006), which corresponds to 50 % of the tree biomass.

Analyzed growth models and increments

Five growth models were fitted: Schumacher, Gompertz, Chapman-Richards, Weibull and Logistic, all of which are widely used for their practicality and satisfactory fits in several forest growth studies (Kiviste *et al.,* 2002), as depicted in Table 1. The current annual increase (CAI), was derived as follows, the mean annual increase (MAI), and the maximum value of CAI (*max CAI*) were calculated using the integral formula of the best adjusted growth model. Based on these values, the technical shift corresponding to the optimum point of maximum biomass growth rate characterized by the intersection of the CAI and MAI, was estimated.

Table 1. Growth and biomass increment equations used.

Growth model	Integral form	Current annual increase (CAI)	Average annual increase (MAI)	*I*
Schumacher	$Y=ae^{-b/X}+\varepsilon$	$\frac{b}{X^2}*ae^{-b/x}$	$\frac{1}{X}a\ e^{-b/X}$	(6)
Gompertz	$Y=ae^{-be^{-cX}}+\varepsilon$	$ace^{-b*e^{cX}}e^{cX}$	$-ae^{-b*e^{cX}}e^{c*X}$	(7)
Chapman-Richards	$Y=a[1-e^{-bX}]^{c}+\varepsilon$	$abc*e^{-bx}*(1-e^{-b*X})^{c-1}$	$acXe^{-bx}(1-e^{-b*X})^{c-1}$	(8)
Weibull	$Y=a\left[1-e^{-bX^c}\right]+\varepsilon$	$abc*X^{c-1}e^{-b*X^c}$	$abX^c e^{-b*X^c}nl(X)$	(9)
Logistic	$Y=\frac{a}{1+e^{b-c*X}}+\varepsilon$	$\frac{ace^{b-c*X}}{(1+e^{b-c*X})^2}$	$\frac{-ae^{b-c*X}}{(1+e^{b-c*X})^2}$	(10)

Y = Biomass increase (kg); *X* = Age in years*; e* = Natural exponential base*;* nl = Natural logarithm; *a, b and c* = Regression parameters; *I* = Identifier.

The growth in *B* and the accumulation of *C* in tons per unit of area (t ha^{-1}) were estimated using equations 11 and 12:

$$B = Y*(N) \qquad (11)$$

$$C = Y*(tC/t)(N) \qquad (12)$$

Where:

Y = Growth model chosen to estimate the B for each species transformed into tons (t ha^{-1})

N = Average number of trees ha^{-1} in the sampling sites

tC/t = Carbon conversion factor

Fitting method and model selection

The adjustment was performed with the full information maximum likelihood method (FIML), using the *MODEL* procedure of the SAS statistical software (SAS Institute, 2008). The best model was chosen based on the level of significance of the parameters ($p<0.05$), the highest adjusted coefficient of determination ($adjR^2$) (13), the minimum root mean squared error (*RMSE*) (14), and bias ($\overline{e}$) (15), as well as the distribution of residuals and the graphical inspection of observed and predicted values (Prodan *et al.,* 1997). The autocorrelation diagnosis was verified with the Durbin-Watson test (Ramírez *et al.,* 2018; Hernández *et al.,* 2020), and the heteroscedasticity, with the White's test (*TW*) (Jiménez *et al.,* 2020).

$$ {}_{adj}R^2 = 1 - \left[\frac{\sum_{i=1}^{n} \left(Y_i - \widehat{Y}_i\right)^2}{\sum_{i=1}^{n} \left(Y_i - \overline{Y}_i\right)^2} \right] * \left(\frac{n-1}{n-p} \right) \qquad (13) $$

$$ RMSE = \sqrt{\frac{\sum_{i=1}^{n} \left(Y_i - \overline{Y}_i\right)^2}{n-p}} \qquad (14) $$

$$ \overline{e} = \frac{\sum_{i=1}^{n} \left(Y_i - \overline{Y}_i\right)}{n} \qquad (15) $$

Where:

${}_{adj}R^2$ = Adjusted coefficient of determination

RMSE = Root mean square error

$\overline{e}$ = Average residual bias

p = Number of parameters to be estimated

n = Number of observations

Y_i = Observed values

$\widehat{Y}_i$ = Predicted values

$\overline{Y}_i$ = Estimated average value

A continuous time autoregressive model, CAR(X), was utilized to correct the autocorrelation problem, based on the proposal of Zimmerman and Núñez-Antón (2001):

$$e_{ij}=\sum\left(d_k .\ P_k^{h_{ij}-h_{ij-k}}\ e_{ij-k}\right)+\varepsilon_{ij} \qquad (16)$$

Where:

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

d_k = 1 for $j>k$, and 0 for $j=k$

P_k = Autoregressive parameter of order k to be estimated

$h_{ij} - h_{ij-k}$ = Separation distance from the "j^{th}" to the "$j\text{-}k^{th}$" observation i when $h_{ij} > h_{ij-k}$

e_{ij-k} = The "$j\text{-}k^{th}$" ordinary residual in the observation i

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

Since most growth models are heteroscedastic (Quiñonez-Barraza *et al*., 2018), this problem was corrected by employing a weighting function on the residuals using a variance power function based on the inverse of the independent variable (Hernández *et al*., 2017; Guzmán *et al*., 2020) and expressed as:

$$y'=y*(1/A^2)^{0.5}$$

Where:

y' = Residuals with corrected weights

y= Residual value of the growth equation

A = Age (years)

Results and Discussion

Sample characteristics

For *P. teocote*, a diameter range between 1 and 53 cm and a total height (*TH*) of 0.3 to 24.2 were estimated. For *P. oocarpa*, the *ND* ranged from 1.5 to 59.8 cm; however, the *TH* ranged from 1.2 to 29 m (1.2 to 29 m) (Table 2).

Table 2. Dasometric characteristics of *Pinus teocote* Schltdl. *et* Cham. and *Pinus oocarpa* Schiede, *Guerrero*, Mexico.

Species	Variable	$\bar{x}$	*SD*	*CV*	*SE*	*Min*	*Max*
P. teocote	*A*	35.6	22.9	64.3	2.39	8	92
	ND	19.9	14.18	71.3	1.48	3.5	53
	TH	10.4	6.34	61.0	0.66	0.3	24.2
	G	0.044	0.052	118.2	0.01	0.0002	0.2124
	V	0.356	0.49	137.6	0.05	0.0027	2.128
	B	242.8	344.8	142.0	35.95	0.7	1547
P. oocarpa	*A*	32.43	24.17	52.2	2.1	4	104
	ND	22.9	15.9	69.5	3.2	2.5	59.8
	TH	14.4	8.3	42.3	1.5	1.2	29
	G	0.060	0.068	114.1	3.6	0.0002	0.2809
	V	0.639	0.8	103.4	0.1	0.0053	3.3589
	B	335.6	473.2	136.3	25.4	1.2	2359

A = Age (years); *ND* = Normal diameter (cm); *TH* = Total height (m); *G* = Basal area (m^2); *V*= Stem volume (m^3); *B* = Aboveground biomass (kg); $\bar{x}$ = Average value; *SD* = Standard deviation; *CV* = Coefficient of variation as percentage; *SE* = Percentage standard error; *Min* = Minimum value; *Max* = Maximum value.

In regard to the biomass area (B), the minimum and maximum values obtained were 0.7 ($ND=3.5$ cm) and 1547 kg ($ND=53$ cm) in *P. teocote.* In *P. oocarpa*, the range was 5 to 2 359 kg of B ($ND=4.6$ and 59 cm, respectively).

Biomass growth function

All models of biomass growth in mature forests of the two *Pinus* species evaluated presented problems of heteroscedasticity ($TW<0.05$); after the residual correction procedure, the logistic model in *P. teocote* continued to present problems of heteroscedasticity. ($TW=0.016$); Schumacher's and Chapman-Richards' models exhibited the same problem in *P. oocarpa* ($TW<0.05$); they were therefore discarded. With the remaining models, we were able to minimize the heteroscedasticity and thus obtained a better distribution of residuals (Guzmán *et al.,* 2020). Of these growth models, the Weibull model exhibited the highest values for $_{adj}R^2=0.73$ and 0.88, the lowest RMSE values (184.2 and 155.9), and an average bias ($\bar{e}$) of 125 and 108.2 kg. It also exhibited values of $TW=0.0720$ and $TW=0.1036$ for *P. teocote* and *P. oocarpa,* respectively (Figure 2), with highly significant parameters ($p<0.0001$), which ensured its selection to predict the growth in B of mature forests of the two *Pinus* species evaluated, as it had better statistical criteria than the rest of the adjusted growth models.

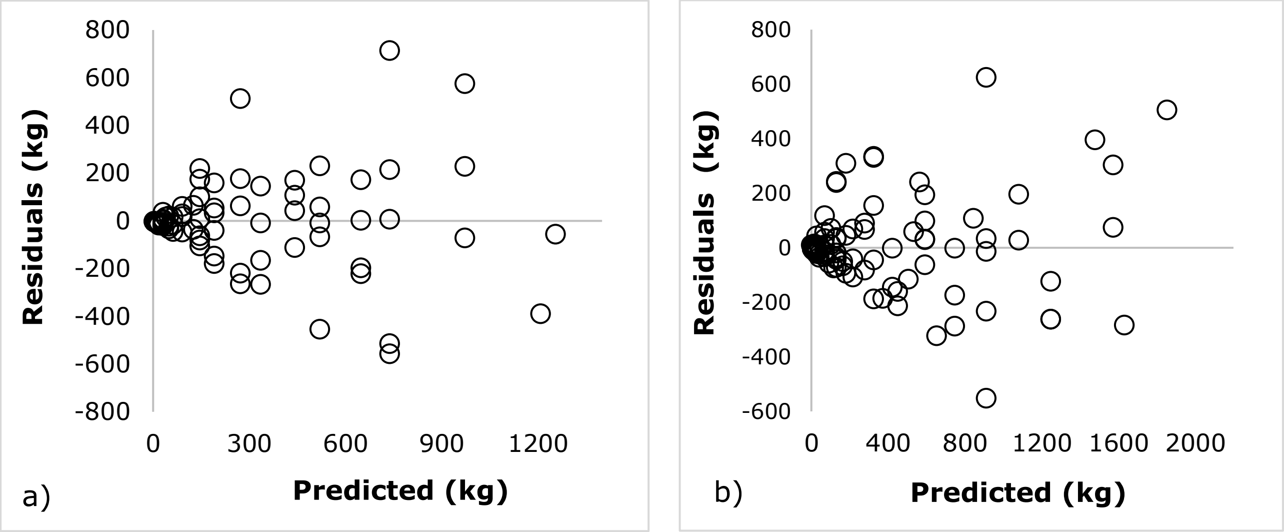


Figure 2. Distribution of residuals (kg) for biomass estimation (kg) in two pinaceae trees in *Guerrero*: a) *Pinus teocote* Schltdl. *et* Cham., b) *Pinus oocarpa* Schiede.

The estimated goodness-of-fit of the five growth models was higher in *P. oocarpa* ($0.80<adjR^2<0.88$) than in *P. teocote* ($0.65<R^2adj<0.73$), which could be due to the variation of biomass in each age category, although this variation was more noticeable in *P. teocote*. Montes de Oca *et al.* (2012) obtained similar values when determining carbon increments for a natural regeneration of *Pinus durangensis* Martínez, with an $adjR^2$ of 0.85 when using the exponential model; the same modeling adjustments occurred in the estimation of the growth in the *B* of a young (12 year-old) plantation of *P. pseudostrobus* Lindl., with values of $adjR^2 = 0.95$ (Méndez *et al.,* 2011). Návar *et al.* (2003) reported an $adjR^2$ of 0.90 with the Clutter model for carbon sequestration in 6 and 20 year-old conifer plantations in *Durango* State, Mexico; these values may be directly attributed to the diameter and age range of trees in young forest plantations (López *et al.,* 2016), with respect to mature forests (with a larger sample size and age group variation) (Aguilar *et al.,* 2016; Murillo *et al.,* 2017).

Table 3. Statistical indicators of growth models in the *B* of *Pinus teocote* Schltdl. *et* Cham. and *Pinus oocarpa* Schiede *Guerrero*.

Ec	*adjR²*	*RMSE*	*ē*	*DW*	*WT*	*Parameter*	*Estimator*	*SE*	*T Value*	*Pr>F*
P. teocote										
6	0.65	203.8	148	2.09	0.0983	*a*	2 064.01	399.4	5.17	<0.0001
						b	90.02	5.669	15.88	<0.0001
7	0.72	185.1	136	1.83	0.0078	*a*	1 445.54	405.2	3.57	0.0006
						b	8.6199	1.067	8.08	<0.0001
						c	0.03639	0.006	5.64	<0.0001
8	0.68	208.3	129	1.74	0.0630	*a*	1 207.94	543.6	2.22	0.0288
						b	0.03252	0.008	3.72	0.0004
						c	5.44790	0.827	6.59	<0.0001
9	0.73	180	125	1.85	0.0720	*a*	1 722.1	997.4	3.73	<0.0001
						b	3.933E-6	5.6E-6	7.70	<0.0001
						c	2.79286	0.4871	5.75	<0.0001
10	0.72	193.8	186	1.78	0.016	*a*	835.004	116.8	7.15	<0.0001
						b	5.854	0.402	14.54	<0.0001
						c	0.11195	0.0121	9.27	<0.0001
P. oocarpa										
6	0.80	211.7	137.4	1.94	0.0587	*a*	2 520.58	325.8	7.74	<0.0001
						b	72.348	4.87	14.85	<0.0001
7	0.84	187.3	129.3	1.97	0.2306	*a*	1 619.03	268.1	6.04	<0.0001
						b	7.0362	0.363	19.35	<0.0001
						c	0.03909	0.0040	9.74	<0.0001
8	0.88	158	117.1	1.87	0.0570	*a*	4 525.89	2 833.6	1.60	0.1132*
						b	0.01223	0.0055	2.20	<0.0300
						c	2.6788	0.3213	8.34	<0.0001
9	0.88	155.5	108.2	1.83	0.1036	*a*	3 186.791	789.5	1.58	0.0300
						b	0.000033	0.603	-24.95	0.004
						c	2.210347	2E-04	4.85	0.002
10	0.84	185.4	114.7	1.92	0.060	*a*	1 509.85	148.9	10.4	<0.0001
						b	4.9016	0.209	23.36	<0.0001
						c	0.0859	0.006	14.17	<0.0001

adjR² = Adjusted coefficient of determination; *RMSE* = Root mean square error (kg); *WT* = White's test; *DW* = Durbin-Watson test; *P>F* = Significance of the model; *a, b, c* = Estimated parameters; *SE* = Standard error (kg); *Pr>T* = Probability value of the Student's t-distribution; *ē* = Average bias (kg); *Non-significant (p>0.05).

The equations for estimating biomass growth are expressed as follows: for *P. teocote*, the generated model was:

$$Y=1722.1(1-e^{-3.933E-6*X^{2.7928}})$$

For *P. oocarpa*, the growth equation was:

$$Y=3186.79(1-e^{-0.000033*X^{2.2103}})$$

Figure 3 shows the projected growth curves in the *B* (kg) with the selected model, as well as their equivalence in *C*. The accumulation of biomass and carbon over time was higher in *Pinus oocarpa*.

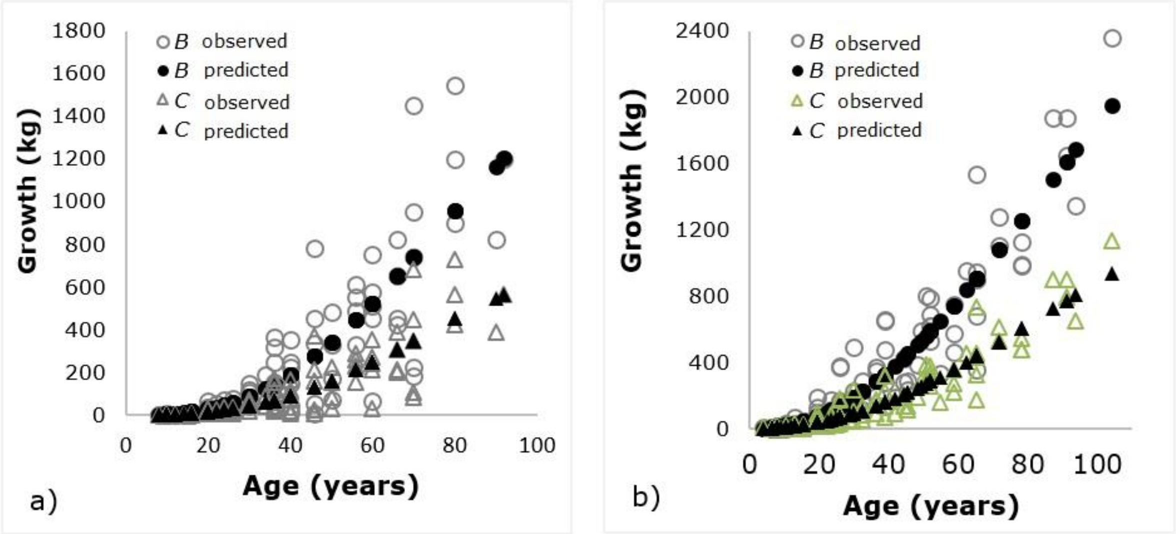
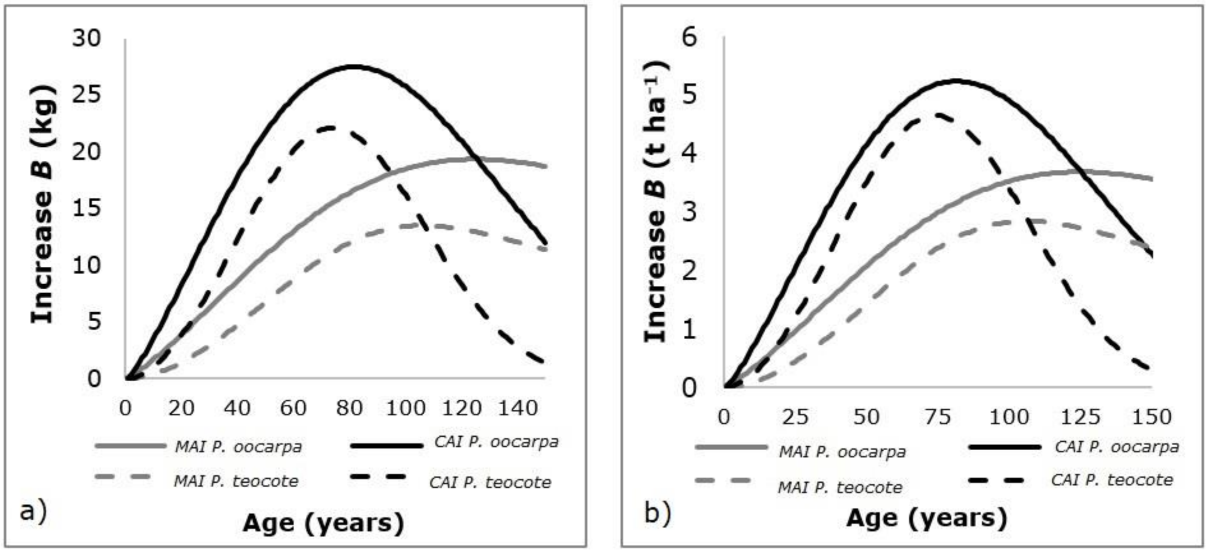


Figure 3. Growth curve in the *B* and *C* of *Pinus teocote* Schltdl. *et* Cham. (a) and *Pinus oocarpa* Schiede(b) in the mountains of *Guerrero*, Mexico.

Estimation of annual increases

The analysis of the results indicates an annual increase of 13.3 kg tree^{-1} in the *B* of *P. teocote* until the technical shift (at 107 years of age); while, in *P. oocarpa* the maximum increments were reached at 126 years (19.7 kg of *B*). The above reflects an uptake of 1.5 times more *B* and *C* between the two species and represents a difference of ~6.4 kg (Figure 4a); the carbon uptake rate is similar to that indicated in 12-year old young forest plantations by Méndez *et al*. (2011), who determined that *P. pseudostrobus* captured on average 1.6 times more carbon than *P. devoniana*, up to the technical shift (12 years); however, the difference was 50.8 kg of *B* between both taxa.



MAI =Mean annual increase (MAI); *CAI* = Current annual increase.

Figure 4. Sequence of the annual increase in *B* in kg (a) and in t ha^{-1} yr^{-1} in *Pinus teocote* Schltdl. *et* Cham. and *Pinus oocarpa* Schiede in the mountains of *Guerrero*, Mexico.

Instant growth (*max CAI*) was 21.93 kg in *P. teocote* at 76 years of age, representing 4.6 t ha^{-1} yr^{-1} of *B* and 2.16 t ha^{-1} yr^{-1} of *C*; for *P. oocarpa*, the *max CAI* value was 27.4 kg at 84 years of age (Figure 4a), which projected to t ha^{-1} yr^{-1} was 5.21 (*B*) and 2.50 (*C*). This would result in increases up to the technical shift (CAI=MAI) of 2.81 and 1.32 t ha^{-1} yr^{-1} of *B* and *C*, respectively, in *P. teocote*; for *P. oocarpa* the increases would be of 3.64 (*B*) and 1.74 (*C*) t ha^{-1} yr^{-1} (Figure 4b).

Figure 5 shows the cumulative projection for B in t ha^{-1}, which could extend outside the limits of biological growth according to the prediction of the selected growth model. Therefore, we should consider as a limit the inflection point when CAI = MAI (technical shift); in this sense, *P. teocote* would reach up to 303.6 t ha^{-1} of B, which represents 142.69 t ha^{-1} of *C*. In turn, in *P. oocarpa* the limit would be 463 t ha^{-1} of *B* (222 t ha^{-1} of C). The above would only be valid if all the trees present per hectare reach the technical turn together.

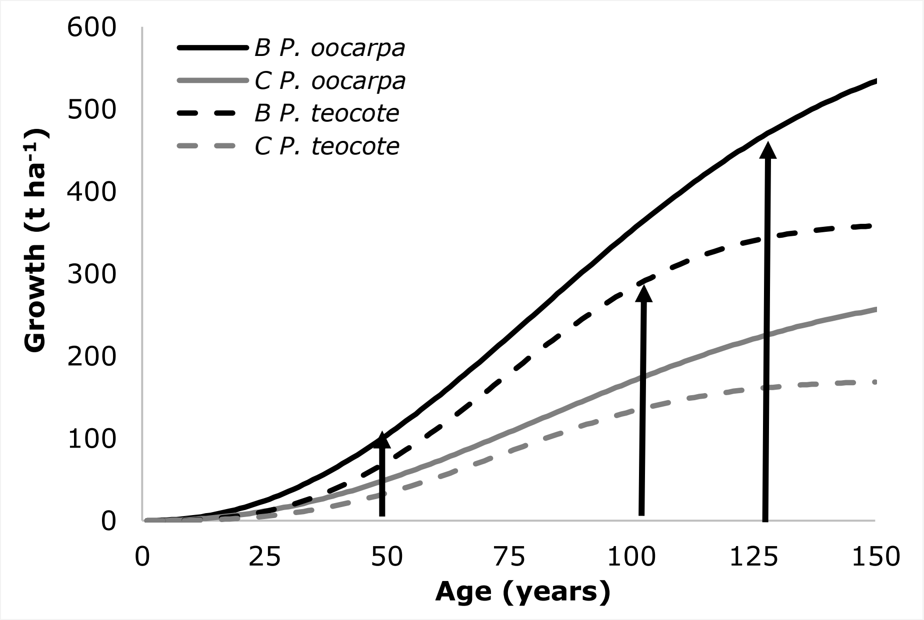


Figure 5. Projection of cumulative growth in t ha^{-1} of *B* and *C* up to the technical shift and base age (50 years) in *Pinus teocote* Schltdl. *et* Cham. y *Pinus oocarpa* Schiede, Mountains of *Guerrero*, Mexico.

When considering as a reference a base age of 50 years, which is commonly used for site index estimations in *Pinus* forests (Vargas *et al*., 2010; Pimienta-de la Torre *et al.,* 2020), it was inferred that *P. teocote* would capture 71 t of *B* ha^{-1} (33 t of C ha^{-1}), and *P. oocarpa*, on average, would accumulate 103 t of *B* ha^{-1}, which represent 49 t of *C* ha^{-1}. These results exceed those obtained by Alberto and Elvir (2008), who reported 39 t *B* ha^{-1} accumulated in highly competitive mature *P. oocarpa* forests in Honduras. However, Rodríguez-Larramendi *et al.* (2016) estimated 172 and 190 t of B ha^{-1} aged up to 120 years in *Pinus patula* Schltdl. *et* Cham. and *Pinus maximinoi* H. E. Moore forests; while Figueroa *et al*. (2010) registered 166 and 186 t ha^{-1} of *B* in 25-year old stands of *P. patula* under thinning; López *et al.* (2016) documented up to 128 t ha^{-1} of *B* in 51 year-old *Hevea brasilensis* (Willd. ex A.Juss.) Müell. Arg. forest plantations; this value is higher than those obtained in the present study. These differences may be attributed to the density (ind ha^{-1}) reflected in competition (crown cover), anatomical conformation or basic wood density of the species (Valencia and Vargas, 2001).

When comparing the results with young forest plantations, Pacheco *et al.* (2007) indicated 37.5 t of *B* for *P. greggi* Engelmn.; Méndez *et al.* (2011) indicated 10.42 t of *B* ha^{-1} for 12 year-old plantations of *P. devoniana* Lindl. and *Pinus pseudostrobus* —figures well below those estimated in this study and directly attributed to the age of the taxa.

According to Villar *et al.* (2004), the vegetation cover and net assimilation rate are the factors that most positively influence the biomass growth of a plant; that is, although two plant species grow under similar conditions, they differ markedly in their ability to grow due to the abundance of water, nutrients and, most importantly, the genetic component.

Conclusions

The trunk analysis technique in combination with basic wood density values allows estimating the growth in biomass area and carbon sequestration in mature stands of *P. oocarpa* and *P. teocote*, which will have an impact on improving forestry interventions adjusted to the forest planning objective, such as carbon inventories. The Weibull growth model presents the best statistics for estimating biomass growth and inferring carbon sequestration for the two species studied. In general, *P. oocarpa* accumulates 1.5 times more biomass and carbon over a longer time interval than *P. teocote* in mature forests in the mountainous region of the state of *Guerrero*.

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Conflict of interest

The authors declare no conflict of interest.

Contribution by author

Juan Manuel Ríos Camey: field data collection, drafting of the manuscript; Oscar Alberto Aguirre Calderón, Eduardo Javier Treviño Garza, Javier Jiménez Pérez, and Eduardo Alanís Rodríguez: drafting, reviewing, proofreading and editing of the manuscript; Héctor Manuel de Los Santos Posadas: statistical analysis and review of the manuscript.

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