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Article

Equations to characterize diameter at breast height growth of *Pinus montezumae* based on increment cores

Ecuaciones para caracterizar el crecimiento en diámetro normal de *Pinus montezumae* usando virutas de incremento

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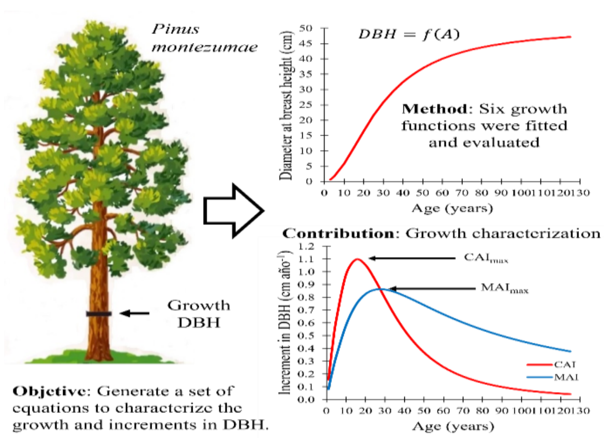
Abstract

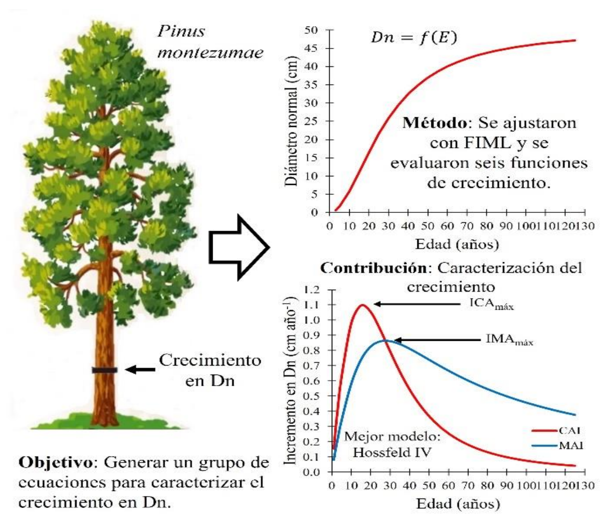
A set of equations to characterize the growth and increments in diameter at breast height (DBH) as a function of age (A) for *Pinus montezumae* in Puebla, Mexico was generated. From radial increment cores collected in the Forest Management Unit 2103 "Teziutlan" 294 pairs of DBH-A observations were processed. Six growth models were fitted. The Hossfeld IV model was selected (R_{2adj} of 0.8328, RMSE of 4.6649 cm and bias of 0.0525 cm). The technical turn was 27.5 years, which corresponds to a maximum mean annual increment of 0.86 cm year^{-1} and a DBH of 23.8 cm.



CAI-MAI, Hossfeld IV model, Technical turn

Resumen

Se generó un conjunto de ecuaciones para caracterizar el crecimiento e incrementos en diámetro normal (Dn) en función de la edad (E) para *Pinus montezumae* en Puebla, México. Se procesaron 294 pares de observaciones Dn-E provenientes de virutas de incremento radial colectadas en la Unidad de Manejo Forestal 2103 "Teziutlán". Se ajustaron seis modelos de crecimiento. Se seleccionó al modelo de Hossfeld IV (R_{2adj} de 0.8328, RCME de 4.6649 cm y sesgo de 0.0525 cm). El turno técnico fue de 27.5 años (IMAmáx de 0.86 cm año^{-1} y Dn de 23.8 cm).



ICA-IMA, Modelo de Hossfeld IV, Turno técnico

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Introduction

Biometric tools in form of mathematical models are necessary for determining the growth of commercially important tree species for timber (Pretzsch, 2009). The growth and increment rates of tree attributes are estimated using growth models, which are the scientific basis for planning silvicultural management regimes and for sustainable harvesting over time (Tamarit-Urias et al., 2021). Therefore, it is important for foresters to have quantitative biometric tools to generate accurate and updated dasometric information on the growth and increment of forest species with commercial interest.

Diameter at breast height (diameter at 1.3 m from the ground) is one of the most important attributes and dendrometric variables of trees, it should be measured to be certain about its size (García-Espinoza et al., 2023), its measurement is easy and direct to perform, and it has a high correlation with other tree and stand attributes (Umemi and Inoue, 2024). For these reasons, it is necessary to develop mathematical equations to adequately model growth and increment in order to make informed decisions for the optimal planning and execution of silvicultural practices.

Diameter at breast height growth models of a particular taxon can be basic components in timber growth and yield systems, contributing to simulate the development and timber production of stands under different silvicultural alternatives (Xu et al., 2014; Moreno et al., 2017; Briseño-Reyes et al., 2020). In addition, they allow predicting the time required for trees to reach a certain dimension in normal diameter and thus to predefine a commercial turn for final harvest (Sánchez-González et al., 2005; Quiñonez et al., 2015; Tamarit-Urias et al., 2021).

In Mexico, diameter at breast height growth models are useful for development and implementation of timber forest management programs because they allow the objective determination of growth rates, current and mean increments, average pass times by diameter category, technical turn or cutting cycle based on the diameters of interest to be harvested (Tamarit-Urias et al., 2021). To generate them it is common to use information on diameter at breast height (DBH) and age (A).

One way to obtain DBH-A data is through sampling sites for operational timber forest inventory. In this regard, Carrillo (2008) states that 3 to 4 dominant trees of the most frequent diameter class should be selected per site, from which the DBH is measured and then a radial increment cores is extracted. By counting the annual growth rings, the current age of the tree at the height of the DBH is determined. This technique is a non-destructive sampling because the trees are not felled, and for the purposes of DBH growth studies, it has a similar precision to the stem analysis technique.

Pinus montezumae Lamb. is a species of the conifer group, with a wide distribution and abundance in Puebla, Mexico; it is of high commercial importance for timber and is used industrially for various purposes. Specimens of this taxon reach heights of 25 to 30 m, with rapid to moderate growth at an average altitude of 2 500 m and an annual rainfall of 800 mm (Perry, 1991; CONAFOR, 2012a). Notwithstanding its importance, studies aimed at generating quantitative biometric tools to model and estimate with certainty the growth and increment in diameter at breast height of this taxon are limited. Therefore, the objective of the present study was to develop models to characterize the growth, current and mean annual increment, as well as the pass times of the diameter at breast height as a function of age for individual trees of *P. montezumae* using information from radial increment cores.

Methodology

The study was conducted in the Forest Management Unit (FMU) 2103 Teziutlan region, located northeast of Puebla, Mexico, at 20° 02' 34" - 19° 36' 34" N and 97° 43' 46" - 97° 22' 23" W. The average altitude is 2,220 m, average annual temperature is 12 to 22 °C, the soils are Luvisol type (CONAFOR, 2012b).

The arboreal stratum is composed mainly of taxa of the genus *Pinus*. *P. montezumae* prevails because of its abundance, in addition to *Quercus* sp. and *Liquidambar styraciflua* that form the type of vegetation called mountain cloud forest (Rodríguez-Acosta y Arteaga-Martínez, 2005).

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DBH and A information from 90 sampling sites was processed. The sites were circular of 1000 m^2, which were located in stands where *P. montezumae* was abundant with dominance ≥ 80 %. At each sampling site, 3 to 4 dominant trees of the most frequent diameter class were selected (Carrillo, 2008).

These specimens were healthy, free of defects and well conformed. The total sample of 294 trees included all categories of diameter at breast height and total height, as well as the different station quality conditions present in the FMU. Each selected tree had its DBH measured in cm with a Forestry Suppliers Inc. diameter tape, model 283D/5m-CSE, graduated in cm and accurate to the millimeter.

To determine the age in years of each specimen, we proceeded based on Hess et al. (2018) and Savidge et al. (2023). Using a Haglöf brand Presler increment borer, a radial increment core was extracted from each selected tree at the height of 1.3 m from ground level and at a depth equal to half of the DBH, so its length was variable and its diameter was 5 mm. Based on Iqbal et al. (2020) and Bakhtina et al. (2020) in each radial increment core the total number of annual growth rings from the center to the periphery was counted.

To the total number of rings counted, 8 were added, which corresponds to the average time in years that trees of this taxon in the study area need to reach the height of 1.3 m. A database was conformed with 294 pairs of DBH-A observations, which was curated to verify logical graphic behaviors and for the respective statistical processing. The descriptive statistics of the DBH-A variables are presented in Table 1.

Box 1

Table 1

Basic descriptive statistics of the variables diameter at breast height and age analyzed

Variable	Mean	Min	Max	SD	CV
DBH, cm	25.98	11.40	62.30	10.68	41.09
A, year	35.53	13.00	123.00	21.37	60.14

Min: Minimum, Max: Maximum, SD: Standard deviation, CV: Coefficient of variation.

Source: Own elaboration using sample data

A preliminary analysis consisting of fitting 16 growth models reported in Kiviste et al. (2002), Burkhart and Tomé (2012) and Panik (2013), showed based on goodness-of-fit criteria that six models (Schumacher, M1; Chapman-Richards, M2; Korf, M3; modified Hossfeld I, M4; Hossfeld IV, M5 and Weibull, M6) were plausible candidates for modeling diameter at breast height growth as a function of age (Table 2).

The general mathematical structure of these models is:

$$DBH_{ij} = f\left(A_{ij}, \alpha_i\right) + \varepsilon_{ij} \text{ con i=1, } \cdots \text{, n} \quad (1)$$

where DBH_{ij} is the j-th observation of the diameter at breast height in cm of tree i assumed as the response variable, A_{ij} is the j-th observation of the explanatory variable corresponding to the age in years of tree i, α_i is the vector of model parameters, ε_{ij} is the error of the j-th observation in tree i which is assumed independent and normally distributed with zero mean and constant variance.

Box 2

Table 2

Base growth models fitted and evaluated to estimate the diameter at breast height of *Pinus montezumae* in FMU 2103, Pue., México.

Mathematical expression of the model	Label
$DBH = \alpha_0 \, exp(-\alpha_1 \, / A)$	M1
$DBH = \alpha_0 \, [1 - exp(-\alpha_1 \, A)]^{\alpha_2}$	M2
$DBH = \alpha_0 \, exp\left(\frac{-\alpha_1}{A^{\alpha_2}}\right)$	M3
$DBH = \frac{A^2}{(\alpha_0 + \alpha_1 \, A)^2}$	M4
$DBH = \frac{\alpha_0}{1 + exp\,(\alpha_1)/A^{\alpha_2}}$	M5
$DBH = \alpha_0 \, [1 - exp(-\alpha_1 \, A^{\alpha_2})]$	M6

DBH: Diameter at breast height, E: Age, α_i parameters to estimate by regression; exp is the exponential function.

Source: Own elaboration using references Kiviste et al. (2002), Burkhart and Tomé (2012) and, Panik (2013)

The statistical analysis consisted of fitting the aforementioned models by regression. The full information máximum likelihood (FIML) method was applied using the Model procedure of the SAS/ETS v statistical program. 9.3 (SAS Institute Inc., 2011).

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To select the best model, the significance of the estimated parameters ($p<0.05$) and the goodness-of-fit statistics were considered: the highest value of the adjusted coefficient of determination (R^2_{adj}), the lowest values of the root mean square error (RMSE) and bias (B), the highest value of the likelihood (logLik) and the lowest value of the Akaike information criterion (AIC).

In the evaluation and identification of the best models a relative rating system was also implemented, on the statistics referred to based on Tewari and Singh (2018) each fit statistic of each model was ranked by assigning consecutive values from 1 to 6 (1 corresponded to the best value of the statistic and 6 to the worst value). A total rank (TR) was obtained for each model by adding the ranks assigned to each of the statistics. By comparing the TRs, the best models were identified, which were those with the lowest TR. In addition, a graphic analysis was made of the congruence and biological realism that each of the models reproduces, through the average curve that each model estimates superimposed on the trend of the observed growth data.

Based on Pretzsch (2009) and, Burkhart and Tomé (2012), for the best model, the respective expressions for: current annual increment (CAI), maximum CAI (CAI_{max}), mean annual increment (MAI) and, maximum MAI (MAI_{max}), which corresponds to the age of technical turn (CAI=MAI), were derived by differential calculus. With the selected model, average growth curve in DBH was constructed, and the CAI, MAI, CAI_{max} and MAI_{max} were calculated and plotted. Finally, the selected model was inverted to generate an expression that allows estimating the pass time (PT), which corresponds to average time in years that a tree requires to pass from a lower diameter category to the next higher one.

Results

All parameters of the fitted models were significant (Table 3). Based on the goodness-of-fit statistics of each model and the respective total ranks (Table 4), it is inferred that the M6, M2 and M5 models are comparatively superior for estimating diameter at breast height a function of age.

Notwithstanding the rating system suggests that M6 model is statistically better, the analysis of the graphical behavior about trend of average growth curve describing each model shows that the M6 model is biologically and comparatively more conservative.

Meanwhile, the same graphical analysis suggests that the M5 model performs better because its behavior is biologically more consistent, reasonable and realistic throughout the time interval analyzed (Figure 1), especially at the maximum ages where the DBH tends to stabilize with a higher asymptotic ceiling. In addition, the site quality in the study region is good, which is why model 5 is considered appropriate.

From the analysis referred to above, it can be deduced that the M5 model, which corresponds to the Hossfeld IV model, has the highest predictive capacity, so it was selected to model the growth of DBH as a function of age for *P. montezumae* trees in the study area.

Box 3

Table 3

Estimated values of the parameters of the evaluated growth models.

M	P	Estimates	SE	t	Pr>|t|*
M1	α_0	60.048650	1.0096	59.48	<0.0001
	α_1	25.348660	0.8792	28.83	<0.0001
M2	α_0	45.938840	0.8487	54.13	<0.0001
	α_1	0.046956	0.0052	8.96	<0.0001
	α_2	2.061518	0.3143	6.56	<0.0001
M3	α_0	59.029850	4.3656	13.52	<0.0001
	α_1	27.381130	11.1634	2.45	0.0147
	α_2	1.029353	0.1462	7.04	<0.0001
M4	α_0	2.330482	0.0873	26.69	<0.0001
	α_1	0.121340	0.0015	83.02	<0.0001
M5	α_0	50.073110	1.7591	28.46	<0.0001
	α_1	6.417781	0.5404	11.88	<0.0001
	α_2	1.905461	0.1786	10.67	<0.0001
M6	α_0	44.500930	0.6447	69.03	<0.0001
	α_1	0.004209	0.0014	3.11	0.0020
	α_2	1.565335	0.0978	16.01	<0.0001

M: Model, P: Parameter, SE: Standard error, t: t value, *Probability level 5% (α=0.05).

Source: Own elaboration with information obtained from the models fitted

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Box 4

Table 4

Goodness-of-fit statistics of the growth models evaluated and total rank obtained for each model

M	R^2_{adj}	RMSE	B	logLik	AIC	TR
M1	0.8268	4.7477	0.0271	-900.91	945.94	18
M2	0.8361	4.6184	0.0378	-892.04	930.20	11
M3	0.8262	4.7551	0.0338	-900.87	947.87	21
M4	0.8219	4.8146	-0.0679	-905.14	954.41	30
M5	0.8328	4.6649	0.0525	-895.07	936.26	16
M6	0.8395	4.5707	0.0556	-888.89	923.91	9

M: Model, R^2_{adj}: adjusted coefficient of determination, RMSE: root mean square error, B: bias, logLik: log likelihood, AIC: Akaike information criterion, TR: total rank.

Source: Own elaboration with information obtained from the models fitted

Box 5

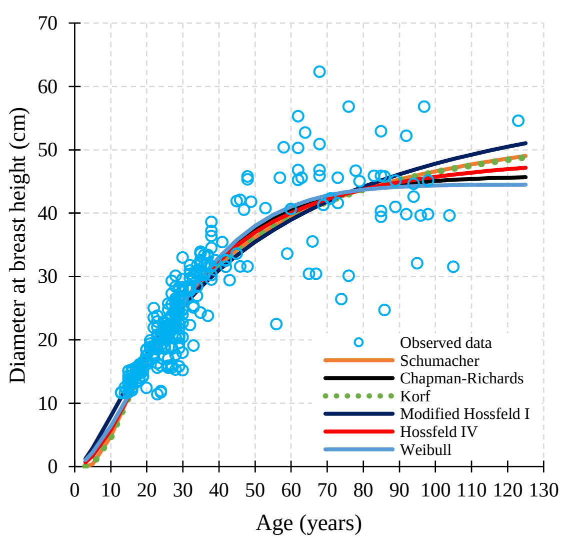

Figure 1

Trends of the average growth curves in diameter at breast height for *Pinus montezumae* estimated with the growth models evaluated against the observed values.

Source: Own elaboration using the data observed in the sample and estimated with the evaluated models

The M5 model had the third best value in the R^2_{adj}, RMSE, logLik and AIC statistics, explains 83.28% of the variability observed in DBH, the mean precision is 4.66 cm and offers a minimum deviation with respect to the observed values of 0.05 cm. In addition, all three parameters (α_i) were highly significant. These attributes ratify that the Hossfeld IV model is adequate to estimate the DBH of individual trees of *P. montezumae*, whose average growth trend and observed values are shown in Figure 2.

The expressions derived from the M5 model to calculate the different increments are presented below.

For the current annual increment (CAI):

$$CAI = \frac{\alpha_0 A^{\alpha_2 - 1} exp\,(\alpha_1)\alpha_2}{(A^{\alpha_2} + \exp(\alpha_1))^2} \quad (2)$$

For the maximum current annual increment (CAI_{max}):

$$CAI_{max} = exp\left(\frac{ln\left(\frac{\alpha_2 - 1}{\alpha_2 + 1}\right) + \alpha_1}{\alpha_2}\right) \quad (3)$$

For the mean annual increment (MAI):

$$MAI = \frac{\alpha_0 A^{\alpha_2 - 1}}{A^{\alpha_2} + \exp\,(\alpha_1)} \quad (4)$$

For the maximum mean annual increment (MAI_{max}):

$$IMA_{max} = exp\left(\frac{ln(\exp(\alpha_1)\alpha_2 - \exp(\alpha_1))}{\alpha_2}\right) \quad (5)$$

Where α_0=50.073110, α_1=6.417781 y α_2=1.905461, ln is the natural logarithm, the rest of the components were previously indicated.

Box 6

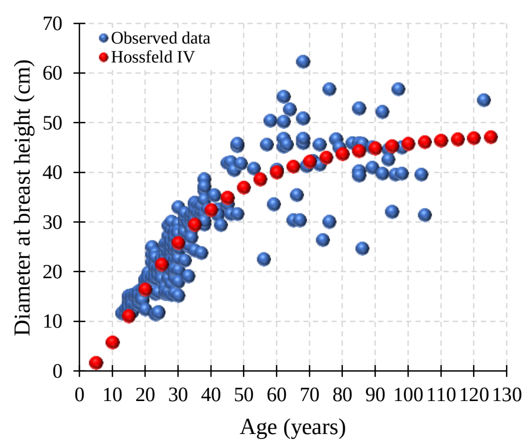

Figure 2

Trend of the growth curve in diameter at breast height estimated by the Hossfeld IV model and growth pattern observed in *Pinus montezumae*.

Source: Own elaboration using the data observed in the sample and those estimated by the selected model

With these expressions it was determined that the CAI_{max} occurs at 15.7 years, with a growth of 1.1 cm yr^{-1} and a DBH of 11.9 cm.

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The technical turn, which corresponds to the MAI_{max} and is equivalent to the age at which the CAI and MAI curves cross, was estimated to occur at 27.5 years (age of greatest growth in DBH) with an increase of 0.86 cm yr^{-1} and a DBH of 23.8 cm (Figure 3). From the point of view of commercial use by the sawmill industry, it would imply letting the forest stands of this taxon grow up to the diameter category of 25 cm so that the volume increases and is profitable.

Hernández (2012) selected the Korf base growth model to estimate the DBH in *P. montezumae* trees in southeastern Hidalgo, Mexico; determined that the technical turn occurs at 41 years of age, at which time a Dn of 26.8 cm is reached, the ICA_{max} was 0.93 cm yr^{-1} at the age of 21 years and the MAI_{max} was 0.65 cm yr^{-1}. Meanwhile, Tamarit-Urias et al. (2021) with stem analysis data determined that growth in DBH in *P. montezumae* for FMU 2101 (Ixta-Popo) in Puebla, Mexico, should be modeled with a dynamic equation generated from applying the generalized algebraic difference approach to the Korf base growth model. For the average growth condition they estimated an CAI_{max} of 1 cm yr^{-1} corresponding to 9.33 cm and is reached at age 14.8 years; the MAI_{max} was 0.79 cm yr^{-1} corresponding to 25 cm of DBH and occurs at age 31.6 years. The differences in the growth parameters indicated can be explained by the fact that the conditions and productive capacity (quality site) are comparatively better in FMU 2103 than in the other two regions mentioned.

Box 7

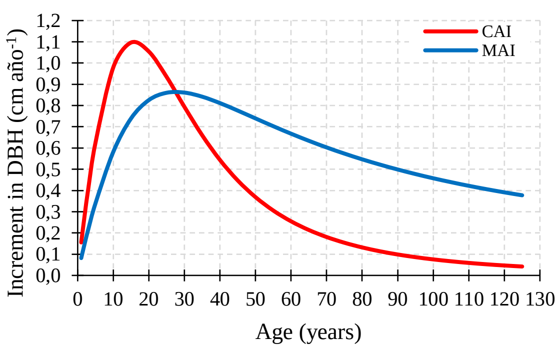

Figure 3

CAI and MAI curves in diameter at breast height for *Pinus montezumae* obtained with the Hossfeld IV growth model in FMU 2103 in Puebla, Mexico.

Source: Own elaboration with the CAI and MAI values generated with the respective expressions of selected Hosfeld IV model

In contrast, Pacheco et al. (2016) for the same taxon in the region of Sola de Vega, Oaxaca, Mexico, determined an CAI_{max} of 1.1 cm yr^{-1} at 13.5 years, while the MAI_{max} was 0.97 cm yr^{-1} at 25.31 years, suggesting that site conditions in that region are slightly better than those prevailing in FMU 2103.

The expression generated to estimate the average time (t) in years at which a commercial dimension of interest is reached in DBH and which is useful to calculate the technological turn, acquired the following mathematical structure:

$$t = exp\left(\frac{ln\left(\frac{DBH}{\alpha_0 - DBH}\right)+\alpha_1}{\alpha_2}\right) \quad (6)$$

Where ln is the natural logarithm, the remainder as defined above.

With this expression, in agreement with Ramírez et al. (2024), it is possible to calculate different commercial harvesting times depending on the industrial use of the raw material to be harvested, such as logs for the sawmill industry, where the minimum sawable diameter is relevant. In practice, it is common to calculate the pass time (PT) in years by diameter category, so that, for the average growth condition in DBH, in an ascending progression, the average PT calculated for this species in the diameter categories from 10 to 40 cm, with 5 cm classes and considering the center of each class, were 4.6, 4.7, 5.1, 6.1, 7.9, 11.4 and 20.3 years, respectively. These PT values show an exponential trend, which is contrary to the commonly assumed assumption that such progression is linear.

Conclusions

An equation based on the Hossfeld IV growth model was derived to model the diameter at breast height growth of individual *Pinus montezumae* trees in FMU 2103 (Teziutlan) in Puebla, Mexico.

Expressions were also derived to calculate the current annual increment, mean annual increment, maximum increments and pass times by diameter category.

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The generated quantitative biometric toolkit is fundamental to infer technological turns and cutting cycles, both basic parameters for technical management in the context of the development and implementation of forest management programs for sustainable timber harvesting of this taxon in the study area. It can also form part of timber growth and yield systems, as well as to make financial projections.

Annexes

Not applicable

Declarations

Conflict of interest

The author declare no interest conflict. He has no known competing financial interests or personal relationships that could have influenced the article reported in this paper.

Author contribution

Tamarit-Urias, Juan Carlos: Generated the research idea, coordinated the research and field work, conducted the documentary research of specialized literature, performed the statistical analysis, interpretation and discussion of results. He wrote, edited, revised and corrected the drafts and the final full version of this scientific article in the format and style of the Ecorfan Journal.

Availability of data and materials

The availability of data is in the possession of the author. They may be made available to the interested party upon request with a justified technical reason to the email: tamarit.juan@inifap.gob.mx

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Abbreviations

CAI	Current Annual Increment.
DBH	Diameter at Breast Height.
FMU	Forest Management Unit.
MAI	Mean Annual Increment.

References

Antecedents

Briseño-Reyes, J., Corral-Rivas, J. J., Solis-Moreno, R., Padilla-Martínez, J. R., Vega-Nieva, D. J., López-Serrano, P. M., ... & López-Sánchez, C. A. (2020). Individual tree diameter and height growth models for 30 tree species in mixed-species and uneven-aged forests of Mexico. *Forests*, 11(4), 429.

García-Espinoza, G. G., Quiñonez-Barraza, G., Aguirre-Calderón, Ó. A., García-Magaña, J. J. & Hernández-Ramos, J. (2023). Ecuaciones de índice de diámetro para plantaciones comerciales de *Pinus pseudostrobus* Lindley en Michoacán, México. *Ecosistemas y Recursos Agropecuarios*, 10(1), 10.

Moreno, P. C., Palmas, S., Escobedo, F. J., Cropper, W. P. & Gezan, S. A. (2017). Individual-tree diameter growth models for mixed Nothofagus second growth forests in southern Chile. *Forests*, 8(12), 506.

Pretzsch, H. (2009). Forest dynamics, growth and yield: From measurement to model. Springer-Verlag Berlin. Heidelberg, Germany. 664 p.

Quiñonez, B. G., De los Santos P. H. M., & Álvarez, G. J. G. (2015). Crecimiento en diámetro normal para *Pinus* en Durango. *Revista Mexicana de Ciencias Forestales*, 6(29), 108-125.

Sánchez-González, M., Tomé, M., & Montero, G. (2005). Modelling height and diameter growth of dominant cork oak trees in Spain. *Annals of Forest Science*, 62(7), 633-643.

Umemi, K., & Inoue, A. (2024). A model for predicting mean diameter at breast height from mean tree height and stand density. *Journal of Forest Research*, 29(3), 186-195.

Xu, H., Sun, Y., Wang, X., Fu, Y., Dong, Y., & Li, Y. (2014). Nonlinear mixed-effects (NLME) diameter growth models for individual china-fir (*Cunninghamia lanceolata*) trees in southeast China. *PLoS One*, 9(8), e104012.

Basics

Bakhtina, S., Yanbaev, Y., Kulagin, A., Redkina, N., Masalimov, I., & Fayzrakhmanov, S. (2020). Dynamics of annual growth of *Pinus sylvestris* on industrial wastes of mining companies. *Journal of Forestry Research*, 32(4), 1385-1393.

Burkhart, H. E., & Tomé, M. (2012). Modeling forest trees and stands. Springer. New York, NY, USA. 458 p.

Carrillo, E. G. (2008). Casos prácticos para muestreos e inventarios forestales. Universidad Autónoma Chapingo. Chapingo, Estado de México, México. 172 p.

Comisión Nacional Forestal (CONAFORa). (2012). *Pinus montezumae* Lamb.

Comisión Nacional Forestal (CONAFORb). (2012). Estudio regional forestal de la unidad de manejo forestal Teziutlán, Puebla. CONAFOR. Puebla, Pue. México. 400 p.

Hess, A. F., Minatti, M., Liesenberg, V., de Mattos, P. P., Braz, E. M., & Costa, E. A. (2018). Brazilian pine diameter at breast height and growth in mixed Ombrophilous forest in Southern Brazil. *Australian Journal of Crop Science*, 12(5), 770-777.

Iqbal, S., Zha, T. S., Hayat, M., Khan, A., Ashraf, M., Ahmad, B. et al. (2020). Spatiotemporal variation and climate change impact on radial growth of chir pine (*Pinus roxburghii*) in a subtropical pine forest in Pakistan. *Applied Ecology and Environmental Research*, 18(4), 4839-4855.

Kiviste, A., Álvarez G. G. J., Rojo-Alboreca, A., & Ruiz, D. G. A. (2002). Funciones de crecimiento de aplicación en el ámbito forestal. Ministerio de Ciencia y Tecnología. Madrid, España. 190 p.

Panik, M. J. (2013). Growth curve modelling: theory and applications. John Wiley & Sons. NJ, USA. 413 p.

Perry, J. P. Jr. (1991). The pines of Mexico and Central America. Timber Press. Portland, OR, USA. 231 p.

Rodríguez-Acosta, M., & Arteaga-Martínez, B. (2005). Índice de sitio para *Pinus chiapensis* (Martínez) Andresen, en los estados de Veracruz y Puebla, México. *Revista Chapingo Serie Ciencias Forestales y del Ambiente*, 11(1), 39-44.

Savidge, R. A., Yuan, X., & Foerster, H. (2023). Gišogenetic variation in white-spruce (*Picea glauca* (Moench) Voss) trees of Yukon Beringia, Canada. *Forests*, 14(4), 787.

Statistical Analysis System (SAS Institute Inc.) (2011). SAS/STAT User's Guide, version 9.3. Cary, NC, USA: Author.

Tewari, V. P., & Singh, B. (2018). Total wood volume equation for *Tectona grandis* Linn F. stands in Gujarat, India. *Journal of Forest and Environmental Science*, 34(4), 313-320.

Supports

Hernández, R. A. (2012). Determinación del turno e índice de sitio para *Pinus montezumae* Lamb., en el sureste del estado de Hidalgo. Tesis profesional. Universidad Autónoma Agraria Antonio Narro. Saltillo, Coah., México. 62 p.

Ramírez, J. A., Marín, A., Gómez, A., & del Valle, J. I. (2024). Growth and yield of *Retrophyllum rospigliosii* pure plantations in the Colombian Andes. *New Forests*, 1-16.

Tamarit-Urias, J. C., Quiñonez-Barraza, G., García-Cuevas, X., Hernández-Ramos, J., & Monárrez-González, J. C. (2021). Ecuación dinámica para estimar el crecimiento en diámetro de *Pinus montezumae* Lamb. en Puebla, México. *Madera y Bosques*, 27(3), e2732180.

Differences

Pacheco, A. G., Santiago, J. W., Martínez, S. D., & Ortiz, B. R. (2016). Análisis del crecimiento e incremento y estimación de índice de sitio para *Pinus montezumae* Lamb. en Santiago Textitlán, Sola de Vega, Oaxaca. *Foresta Veracruzana*, 18(2), 21-28.

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