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Research Article

Estimating dendrometric variables, volume and carbon from stump diameter for *Pinus arizonica* Engelm. in northern Mexico

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Abstract

It is noteworthy that in the last decade, there has been an increase in the number of studies predicting normal diameter, total height, and stem volume based on stump dimensions. Therefore, the objectives were: a) to determine the mathematical model that best estimates normal diameter, total height, stem volume, and captured carbon as a function of stump diameter for *Pinus arizonica* Engelm. in northern Mexico; and b) to generate mathematical models through data processing in the Microsoft Excel program. Using a targeted sampling design, we selected 264 *Pinus arizonica* Engelm. trees to generate the database. The development of prediction models for normal diameter, total height, total tree volume, and captured carbon as a function of stump diameter was carried out using the Microsoft Excel database management package. The fit's adequacy was analyzed based on residuals and statistics such as the root mean square error, the adjusted coefficient of determination, and the coefficient of variation. Model fits indicate a linear trend for the normal diameter variable, while for total height, the model turned out to be logarithmic. As for total tree volume and captured carbon, the relationship is exponential in relation to stump diameter. The R^2_{adj} fits were highly reliable for estimating normal diameter, total tree volume, and captured carbon, with values exceeding 95%. The development of prediction models using Microsoft Excel is viable according to the results presented here. The tested techniques can be replicated by forestry technicians, environmental inspectors, and forest landowners who do not have specialized knowledge in the generation prediction models.

Keywords: dendrometric variables; linear models; mathematical models; Microsoft Excel; *Pinus arizonica* Engelm; prediction models; stump diameter

Introduction

Timber harvesting has been significant for society as it has granted various benefits. Forests are valued from an economic perspective based on the proportion of volume they produce in the cutting cycle or planning

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period (Robinson and Wood, 1994). Therefore, it is essential to understand and comprehend volumetric stocks, height, and diameter of a stand to enable sustainable management. On the other hand, there are phenomena that lead to the detriment of forest vegetation, such as illegal logging, fires, and pests (Pompa-García *et al.*, 2011). However, when harvests are carried out, only the tree stumps are left as evidence. This evidence allows for the reconstruction of the size of the removed trees in terms of their diameter, height, and volume (Quiñónez *et al.*, 2012). Therefore, developing mathematical prediction models enables the estimation of removed stocks, the valuation of trees, and the generation of historical records of forest management activities (Corral-Rivas, 2007; Westfall, 2010).

It is noteworthy that in the last decade, there has been an increase in the number of studies predicting normal diameter, total height, and stem volume based on stump dimensions (Martínez-López and Acosta-Ramos, 2014; García-Cuevas *et al.*, 2017; Flores *et al.*, 2019). In Mexico, most of the efforts have been focused primarily on conifers, with the development of rigorous and robust mathematical models that are challenging for forestry technicians, environmental inspectors, or forest owners to replicate or generate. Therefore, it is essential to have tools based on statistical procedures that are easy to use with basic database packages, allowing for the estimation of normal diameter (*dn*), total height (*h*), stem volume, biomass, and even carbon in relation to stump diameter (*dt*) (Jenkins *et al.*, 2004).

Based on the above, the objectives of this study were: a) to determine the mathematical model that best estimates normal diameter, total height, stem volume, and captured carbon as a function of stump diameter for *Pinus arizonica* Engelm. in northern Mexico; and b) to generate these mathematical models by processing data in the Microsoft Excel program, with the purpose of facilitating model adaptation by forestry technicians, environmental inspectors, and forest owners.

Materials and Methods

Study location

The study was conducted on four private forest properties located in the municipality of Guachochi, in the southwest of the state of Chihuahua, Mexico. These properties are situated within the physiographic province of the Sierra Madre Occidental, between the coordinates 26°55'33.28"N 107° 8'26.23"W and 26°45'45.69"N 107° 7'15.97"W. The area corresponds to a cold coetaneous temperate forest dominated by *Pinus arizonica* Engelm. (> 90% of the standing trees). The soils in this region are classified as eutric cambisol, eutric planosol, and eutric regosol, with a medium to fine texture (INEGI, 2014). The climate is classified as C(E)(w2)(x'), which corresponds to a humid, semi-cold climate, with an average annual temperature ranging from 5 to 12 °C and an average annual precipitation of 621.3 mm (INEGI, 2008).

Data collection and database

Using a targeted sampling design, we selected 264 *Pinus arizonica* Engelm. trees to generate the database, these trees had a normal diameter that ranged between 7.60 and 67.10 centimeters (cm) and heights that ranged between 2.50 and 25.30 meters (m), as shown in Table 1. These trees exhibited the following characteristics: straight and single stem, exceptional natural pruning, full canopy, and no evidence of pests or diseases. With this information, a comprehensive database was created, encompassing all diameter and height categories present in the study area. Each tree had its stump diameter (dt) measured at a height of 10 cm, normal diameter (dn) measured at a height of 1.3 m above ground level using a five-meter Forestry Suppliers Inc® diameter tape, and total height (h) measured using a Suunto® PM5-1520 hypsometer.

Table 1. Descriptive statistics of the *Pinus arizonica* Engelm. Database

Variable	Max	Min	Average	Standard deviation
dt	74.10	10.40	33.35	15.67
dn	67.10	7.60	29.05	14.62
h	25.30	2.50	14.07	5.03
vrtacc	3.90	0.01	0.72	0.80
cc	1240.93	5.83	256.05	278.28

dt = Stump diameter (cm); dn = Normal diameter (cm); ht = Total height (m); Ttvwb = Total Tree volume with bark (m^3); and, cc = Carbon content (kg).

The stem volume equation used for the study species was previously developed by the Regional Forest Management Unit (UMAFOR 0807) in the municipality of Guachochi and is represented by the following expression [1]:

$$\text{Ttvwb} = \alpha_0 * dn^{\alpha_1} * h^{\alpha_2} \qquad [1]$$

Where: $\alpha_0 = 0.0000722$; $\alpha_1 = 1.8460601$; $\alpha_2 = 0.9766791$; dn = normal diameter; and, h = total height.

The captured carbon equation was selected based on a previously developed allometric model for *Pinus arizonica* Engelm. species. The relationship is as follows [2]:

$$C = \alpha_0 + (\alpha_1\, dn) + (\alpha_2\, dn^2) + ((\beta_0\, dn^2)\, h) \qquad [2]$$

Where: $\alpha0 = 11.5090$; $\alpha1 = -3.1229$; $\alpha2 = 0.3100$; ß0 = 0.0004; dn = normal diameter; and, h = total height.

Models used

The development of the prediction models for normal diameter, total height, total tree volume, and captured carbon as a function of stump diameter was carried out using linear regression models obtained with the Microsoft Excel database management package. These models are described in Table 2.

Table 2. Models used to predict normal diameter, total height, total tree volume, and captured carbon from stump diameter

Equation	Model
$dn = a + b(dt)$	1
$dn = a + b(dt) + c(dt)^2$	2
$h = a + b(dt) + c(dt)^2$	3
$h = a + b\ln(dt)$	4
$ttvwb = a + b(dt) + c(dt)^2$	5
$cc = a + b(dt) + c(dt)^2$	6

dt = Stump diameter; dn = Normal diameter; h = Total height; Ttvwb = Total tree volume with bark; cc = Carbon content; and, a, b, and c = Parameters to be estimated.

The goodness of fit was assessed based on the residuals and three commonly used statistics in biometric model comparison (Diéguez *et al.*, 2003; Corral *et al.*, 2007; Pompa-García *et al.*, 2011): root mean squared error [3], adjusted coefficient of determination [4], and coefficient of variation [5]:

$$RMSE = \sqrt{\frac{\left[\left(\sum_{i=1}^{n}\left(Y_i - \hat{Y}_1\right)\right)^2\right]}{n-p}} \qquad [3]$$

$$R_{adj}^2 = 1 - \left[\frac{\sum_{i=1}^{n}\left(Y_i - \hat{Y}_1\right)^2}{\sum_{i=1}^{n}(Y_i - \bar{Y}_1)^2}\right]\left(\frac{n-1}{n-p}\right) \qquad [4]$$

$$CV = \sum_{i=1}^{n} \frac{\frac{(yi - \bar{yi})^2}{n-1}}{\bar{y}} \qquad [5]$$

The root mean squared error indicated the accuracy of the estimations; the adjusted coefficient of determination reflected the total variability explained by the model, based on the total number of parameters to be estimated; the coefficient of variation explained relative variability with respect to the mean, which is useful for a quick comparison of the proposed models (Diéguez *et al.*, 2003). Similarly, residual values were graphically analyzed against predicted values to identify outliers or any systematic trend (Pompa-García *et al.*, 2011); this option is very practical for assessing the fit of the aforementioned models

Results and Discussion

Normal Diameter-Stump Diameter Relationship

The values of the model estimators for the relationship between normal diameter and stump diameter are shown in Table 3. The R^2_{adj} values were equal in both models; however, Model 2 has a non-significant parameter, which is also an indicator for model selection. Additionally, Model 1 had a lower root mean squared error. Therefore, Model 1 was found to predict the normal diameter of *Pinus arizonica* Engelm. more effectively.

Given the simplicity of the linear model and considering the goodness-of-fit statistics, Model 1 is the most suitable for estimating normal diameter from stump diameter for *Pinus arizonica* Engelm., with an R^2_{adj} value of 0.9976. Flores *et al.* (2019) identified that linear models explain the relationship between normal diameter and stump diameter with an R^2_{adj} of 0.98. García *et al.* (2016) also found that a simple linear equation satisfactorily explains the relationship between stump diameter and normal diameter for *Abies religiosa* (Kunth) Schltdl. et Cham. On the other hand, Quiñonez *et al.* (2012) indicate that parabolic models yield good results, but the parameter accompanying the squared variable takes values close to zero, indicating its limited contribution to the model.

Regarding the coefficients of the employed parameters, those generated for Model 1 are significant ($p \leq 0.000$), while the same is not the case for the parameter c in Model 2 ($p=0.482$). García *et al.* (2016) advise against selecting models that do not have significance in any of their parameters.

Table 3. Parameter values and goodness-of-fit statistics for the models used for the normal diameter-stump diameter relationship

Model	RMSE	R^2	R^2_{adj}	CV	Parameter	Estimator	Standard Error	T value	P value
1	0.0127	0.9976	0.9976	0.5027	a	-2.0307	0.1048	-19.385	0.000
					b	0.9321	0.0028	327.741	0.000
2	0.1011	0.9976	0.9976	0.5029	a	-2.1596	0.2112	-10.227	0.000
					b	0.9403	0.0121	77.604	0.000
					c	-0.0001	0.0002	-0.703	0.482

Figure 1 displays the trend of the fit for Model 1, which exhibited the best statistics. Furthermore, the distribution of errors does not follow a defined pattern, suggesting that the model does not exhibit heteroscedasticity issues. The range of residual values is narrow in all cases. Corral-Rivas *et al.* (2007) demonstrated through residual plots that the linear model exhibits an appropriate distribution for pine species in northern Mexico, with no discernible trends or heteroscedasticity. The same scenario was observed in this analysis, indicating that the use of a linear model, generated in the Microsoft Excel program, is sufficient for accurately predicting the normal diameter of *Pinus arizonica* Engelm.

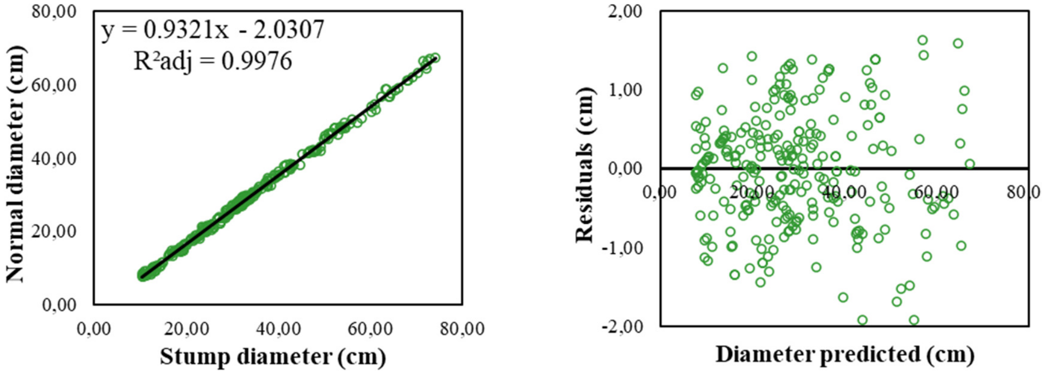

Figure 1. Fit of the selected model and residual values against predicted values

Total height-stump diameter relationship

The parameter values and goodness-of-fit statistics for the relationship between total height and stump diameter are presented in Table 4. The R^2_{adj} values were similar in both models; however, Model 3 has a non-significant parameter, and the root mean squared error (RMSE) is higher. Therefore, the model with the better fit for *Pinus arizonica* Engelm. Was Model 4. García-Cuevas *et al.* (2017) used the modified Schumacher equation to predict the height of *Abies religiosa* (Kunth) Schltdl. et Cham. based on stump diameter. The parameter estimation values indicate that the equation is valid, as it shows low RMSE and a high adjusted R^2, explaining 93.5% of the variation in the observed data. For his part, Martínez-López y Acosta- Ramos (2014) found that a power model is suitable for predicting the total height of *Quercus laurina* Humb. & Bonpl. in relation to stump diameter with an adjusted R^2 of 0.9711. In both cases, the fit is superior to that estimated with the logarithmic model used in this study.

Table 4. Parameter values and goodness-of-fit statistics for the models used for the total height-stump diameter relationship

Model	RMSE	R^2	R^2_{adj}	CV	Parameter	Estimator	Standard Error	T value	P value
3	0.2236	0.8220	0.8213	0.3248	a	-0.0883	0.6076	-0.145	0.885
					b	0.5869	0.0349	16.832	0.000
					c	-0.0040	0.0004	-8.998	0.000
4	0.0889	0.8290	0.8283	0.3244	a	-16.5921	0.8695	-19.082	0.000
					b	9.0452	0.2538	35.638	0.000

Figure 2 illustrates that the predicted values against the residuals of Model 4 for the total height and stump diameter relationship did not exhibit heteroscedasticity issues. Regarding this, it was found that the model accurately predicts height estimations. The 15 m height category showed an underestimation of -0.01 m, and the 25 m height category had an overestimation of 2.07 m, while the remaining categories had errors of ±0.90 m. On the other hand, Flores *et al.* (2019) indicate that the distribution of residuals does not follow a defined pattern, suggesting that the height prediction model for *Pinus pseudostrobus* Lindl. does not exhibit heteroscedasticity issues. This aligns with the findings in this analysis, where the dispersion of residuals was irregular with the logarithmic model.

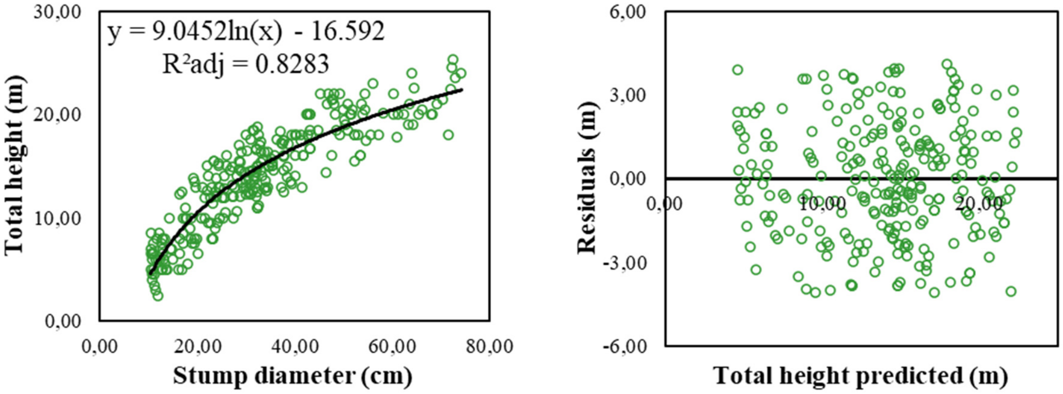

Figure 2. Fit of the selected model and residual values against predicted values

Total tree volume-stump diameter relationship

The parameter values and goodness-of-fit statistics for the relationship between total tree volume and stump diameter are presented in Table 5. Model 5 had an R^2_{adj} of 0.9808 and a low RMSE, as well as an acceptable coefficient of variation. Furthermore, all parameters were significant. Therefore, it is considered that this model adequately predicts the total tree volume for *Pinus arizonica* Engelm. Corral-Rivas *et al.* (2007) estimated tree volume with high precision using an allometric equation. The R^2_{adj} value was 0.912 with an RMSE of 0.131. In contrast, Dieguez *et al.* (2003) and Quiñonez *et al.* (2012) found that the best model for predicting stem volume is logarithmic, with R^2_{adj} values of 0.90 to 0.96, respectively. The values estimated by our study are superior with the use of a power model developed in the Microsoft Excel program.

Table 5. Parameter values and goodness-of-fit statistics for the models used for the total tree volume-stump diameter relationship

Model	RMSE	R^2	R^2_{adj}	CV	Parameter	Estimator	Standard Error	T value	P value
5	0.2474	0.9809	0.9808	1.11	a	0.0825	0.0323	2.552	0.011
					b	-0.0143	0.0019	-7.700	0.000
					c	0.0008	0.0000	34.614	0.000

The distribution of residual values relative to predicted values exhibited heteroscedasticity issues. Therefore, the problem associated with total tree volume was corrected using a power function of residual variance. The estimators of the system are significant ($p < 0.05$). The parameters were estimated and programmed using the procedure shown in [6]:

$$\text{Res cor Ttvwb} = \frac{\text{Res Ttvwb}}{[(dn^2\,h)]^{0.5}} \qquad [6]$$

Figure 3 depicts the trend of the fit for the total tree volume model, which suggests good statistical results. It displays the predicted values against the residuals obtained with the model. After the heteroscedasticity correction, the error distribution does not exhibit a defined dispersion, suggesting that the model does not have heteroscedasticity issues. On the other hand, Corral-Rivas *et al.* (2007) used weighted linear and nonlinear least squares methods to correct the heteroscedasticity issue observed in the volume-stump diameter relationships.

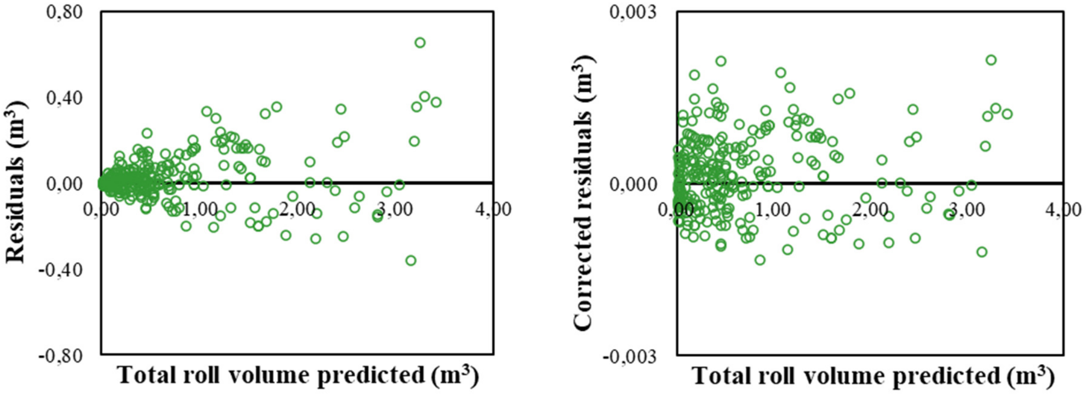

Figure 3. Heteroscedasticity uncorrected (left) and corrected (right) in the system of equations to predict total tree volume

Captured carbon-stump diameter relationship

Model 6 had an R^2_{adj} of 0.9971 and a low RMSE, as well as an acceptable coefficient of variation. Furthermore, all parameters were significant. Therefore, it is considered that this model adequately predicts the captured carbon in the studied species. The values are shown in Table 6. The estimation based on stump diameter (dt) can be used to calculate biomass, and even carbon (Jenkins *et al.*, 2004). However, these analyses have not been widely developed in Mexico, as studies have been primarily focused on estimating the main stem volume.

Table 6. Parameter values and goodness-of-fit statistics for the models used for the captured carbon-stump diameter relationship

Model	RMSE	R^2	R^2_{adj}	CV	Parameter	Estimator	Standard Error	T value	P value
6	0.1717	0.9971	0.9971	1.09	a	19.9298	4.3753	4.555	0.000
					b	-4.2300	0.2511	-16.849	0.000
					c	0.2780	0.0032	86.898	0.000

In Figure 4, the trend of the captured carbon model fit is shown, which suggests good statistical results. Predicted values are plotted against the residuals obtained with the model.

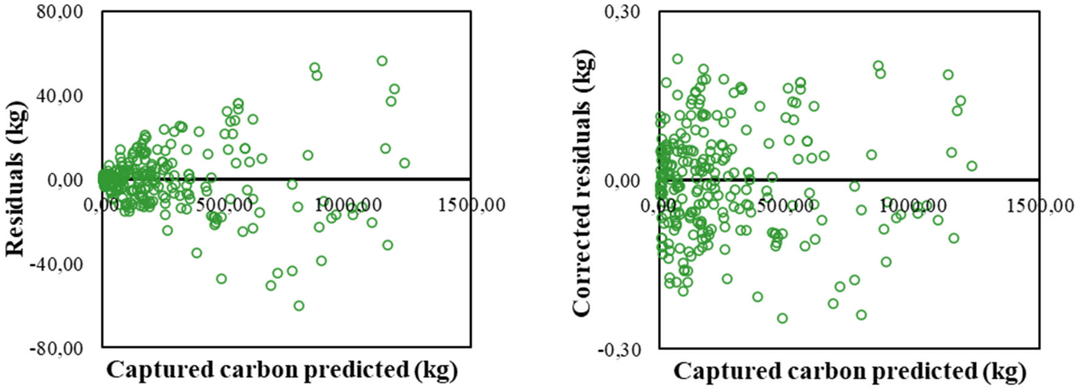

Figure 4. Heteroscedasticity uncorrected (left) and corrected (right) in the system of equations to predict captured carbon

After the heteroscedasticity correction, the error distribution does not exhibit a defined dispersion, suggesting that the model does not have heteroscedasticity issues. The equations generated for the species under study have a solid statistical basis and their application in the region of origin of the data is suggested. This would make it easier for forestry technicians and producers to estimate the dimensions of felled trees using only the stump as a reference.

Conclusions

The model fits indicate that there is a linear trend for the variable normal diameter, while for total height, the model turned out to be logarithmic. As for total tree volume and captured carbon, the relationship is exponential in relation to stump diameter. The R^2_{adj} fits were highly reliable for estimating normal diameter, total tree volume, and captured carbon, with values exceeding 95%. On the other hand, tree height can be estimated with a logarithmic model with an accuracy exceeding 80%.

The relationships generated are relevant for reconstructing scenarios in areas affected by natural conditions or adverse effects within the study area. This information is useful for determining individual dimensions, total tree volume, and captured carbon of *Pinus arizonica Engelm.*

The development of prediction models using Microsoft Excel is viable according to the results presented here. In this regard, the tested techniques can be replicated by forestry technicians, environmental inspectors, and forest landowners who do not have specialized knowledge in the generation of biometric prediction models.

Authors' Contributions

Conceptualization of the research idea, designing the experiment, and writing-original draft preparation, A.K.V.F. and J.R.S.; formal analysis, validation and discussion, J.R.S.; resources, data curation and writing-review and editing, A.K.V.F., J.R.S. and J.H.S.; supervision, J.H.S. and M.P.G. All authors read and approved the final manuscript.

Ethical approval (for researches involving animals or humans)

Not applicable.

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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