Prediction of the normal diameter, height and volume from the stump diameter in tropical species

Xavier García Cuevas[1]

Jonathan Hernández Ramos[1]

Adrián Hernández Ramos[2*]

Gerónimo Quiñonez Barraza[3]

Juan Carlos Tamarit Urías[4]

Guadalupe Geraldine García Espinoza[5]

[1]Campo Experimental Chetumal, CIR- Sureste, INIFAP. México.

[2]Campo Experimental Saltillo, CIR-Noreste, INIFAP. México.

[3]Campo Experimental Valle de Guadiana, CIR- Norte Centro INIFAP. México.

[4]Campo Experimental San Martinito, CIR Golfo-Centro, INIFAP. México.

[5]Programa de Posgrado. Universidad Autónoma de Nuevo León. México.

[*]Autor por correspondencia, correo-e: adrian.hernandezr90@gmail.com

Abstract

In the control and supervision of forest management, the estimation of the diameter at breast height is necessary to characterize the original stand and from this estimate, the extracted volumes. When the tree no longer exists, it is not possible to know the dimension of the diameter at breast height (d), height (h) and volume (v). These variables can be estimated based on stump diameter (dt). This allometric relationship can be used to calculate the missing volumes (v). Therefore, the aim of this research was to develop predictive equations relating dt-d, dt-h and dt-v for eight tropical species (Mahogany, Red cedar, *Chacah, Chechem, Ramón, Sacchacah, Chicozapote* and *Tzalam*) of Quintana Roo, through a selective sampling and direct measurement of 1,169 pairs of dt-d data, and indirect measurement of the height (h) of trees. All possible heights and diameter categories in different growth conditions were included. By using the ordinary least squares method, a linear model was fitted, and one for predicting the nonlinear diameter at breast height and other to predict the nonlinear volume. Based on the level of significance of the model parameters, their estimates of goodness of fit, the distribution of residuals, and the predictive ability of them, it can be inferred that these are valid to predict the d, h and v as a function of dt. All models explained the data variability.

Key words: Allometry, cuts, equations, tropical species, forest management, regression.

Introduction

In the quantification of clandestine cuttings or revisions in areas under management, knowing the normal diameter (d) and volume (v) is basic to characterize the original tree structure and from this, to estimate the extracted volumes (López *et al*., 2003; Pompa *et al*., 2011) and even the biomass or the amount of captured carbon.

This is achieved through allometric models that estimate the d as a function of the stump diameter (dt) and a volume rate that depends on the d or dt (Diéguez *et al.,* 2003). The estimation of d as a function of dt can be done by regression processes and thus be used to calculate the volumes (Jenkins *et al.,* 2004; Pompa *et al*., 2011), as Diéguez *et al.* (2003) did, who adjusted d and v equations for six forest species in Galicia, Spain, using linear and allometric models transformed by logarithms. The results obtained showed adequate relationships between variables, but it was the dt variable that best predicted the dependent variables indicated, in addition to the inclusion of stump height (ht), no improvement was obtained in the predictions.

Benítez *et al.* (2004) carried out a study in plantations of *Casuarina equisetifolia* L. of the province of *Camagüey*, Cuba. In this work a mathematical model was developed that allowed to determine the d from $dt.$ The logarithmic equation $Ln(d) = -0.249 + 1.021 Ln(dt)$ accurately explains 94 % of the variability of the information.

Bava and López (2006) with data of *d, dt* and total height *(h)* adjusted d predictor models in in regard to the other two variables. Given the heteroskedasticity found, the procedure was repeated with the transformed variables and they selected a logarithmic model of the form:

$$Log(d) = a + bLog(dh) + cLog\left(\frac{dh}{h}\right)$$

Where:

Log = Logarithm

d = Normal diameter

dh = Diameter at stump height

h = Total height

This model allows to determine the *d* of the trees that were cut from the dimensions of the stump, and can be used both to determine the original structure of the forest and for the characteristics of an already realized harvest.

Corral *et al.* (2007) suggest a linear adjustment for the first classes of d, due to the good results for pine species of northern Mexico with the model:

$$dn = \beta_0 + \beta_1 dt$$

Diéguez *et al.* (2003), Jenkins *et al.* (2004) and Pompa *et al.* (2011) calculated the *d* in linear function of the *dt*, but did not include the *ht* as an explanatory variable because it considers that the *dt* invariably occurs at a constant *ht* of 0.3 m, which is not always the case, especially with trees in rugged topographies or various techniques of felling used.

The same authors indicate that the variations in *ht* and the dendrometric type of the first log of the tree should be considered when adjusting models of the stump to *d* ratio and, because of their tapering, it is necessary to test nonlinear models with *ht* as predictive variable. It has been shown that the truncated neophyte adequately

models the stump (Díaz *et al.,* 2007; Pompa *et al.,* 2011), and has even been recommended for biomass estimation (Navarro *et al.,* 2000).

To achieve this, the authors considered the stump as the portion of the tree at ground level to a height less than or equal to 1.3 m (Raile, 1977), because this section follows a dendrometric pattern of the truncated neiloid type. Since *h* is related to *ht*, that is, when the normal diameter (*d*) is equal to the diameter of the stump (*dt*), it is expected that *ht* = 1.3 m, whereby:

$$\frac{dn}{dt} = \frac{1.3}{ht}$$

that is, empirically there is:

$$d = \beta_0 dt \left(\frac{1.3}{ht}\right)^{\beta_1}$$

Where:

β_0 and β_1 = Coefficients to be determined through regression

The first parameter of the function describes the ratio of *d* to *dt* along this section of the shaft, while the latter represents the shape according to the dendrometric characteristics of the neiloid. It is expected that this model will meet the condition that *dt* = *d* when *ht* = 1.3, for which β_0 must be close to 1.

Quiñones *et al.* (2012) adjusted 12 mathematical models to predict *d* from *dt* for *Pinus arizonica* Engelm., *P. ayacahuite* Ehrenb. ex Schlitl., *P. durangensis* Martínez, *P. leiophylla* Shiede ex Schltdl. & Cham., *P. teocote* Shiede ex Schltdl. & Cham., and *Quercus sideroxyla* Humb. & Bonpl. in *Durango*, Mexico. For this, they used linear

and nonlinear models. The adjustment of the models indicates that there is a linear trend between the variables *d* and *h*, as a function of *dt*; while for *v* the relation is logarithmic. The equations obtained can be applied in the reconstruction of scenarios after a forestry intervention or the occurrence of catastrophic natural phenomena. The equations obtained for the species are of the form:

$$Ln(d) = a + bLn(dt)$$

To predict height as a function of stump diameter, literature is scarce. Quiñonez *et al.* (2012) fitted the models recommended by Diéguez *et al.* (2003), Benítez *et al.* (2004) and Corral *et al.* (2007), who propose a linear or exponential relationship between the *dt* and the *dn* or *v* of the trees. The best results were obtained with the following expression:

$$h = \beta_0 + \beta_1 dt$$

Given the data distribution of the functional relationship between *dt* and *h,* it is also suggested to test a relation with a non-linear parameter with these formula:

$$at = \beta_0 + \beta_1 dt^{\beta_2}$$

For volume, forest engineers use the regression of the volume of the trees on their diameter, which means that by measuring the diameter (independent variable) and replacing its value in a relation defined by the tree class, the volume is obtained and even without calculations, appreciate the volume by using the graphs of the dependence function, volume = *f* (diameter) (Prodan *et al.,* 1997).

For biological data such as volume, the heteroscedasticity of the residues almost

always corresponds to a power ratio between the residual variance and the size of the trees. It is assumed, then, that among the explanatory variables of the weighted regression, there is one (typically the diameter of trees) such that v is a power function of such variable. Without loss of generality, it can be assumed that this variable is dt, so that:

$$v = \beta_0 dt^{\beta_1} \text{ (Picos and Cogolludo, 2008).}$$

Where:

$\beta_0 > 0$

$\beta_1 \geq 0$

Consequently, the power function is of the form:

$$f(x) = ax^n$$

Where:

β_0 = Real number, different from 0

β_1 = Natural number, different from 1 (Picard *et al*., 2012)

This model is regularly used, known as allometric model (Prodan *et al*., 1997).

The aim of this work was to develop equations that describe the relationship between normal diameter (d), height (h) and volume (v) with the diameter of the stump (dt) of eight tropical forest species in *Quintana Roo*.

Materials and Methods

Around 20 species are commercially important in the forest harvests of *Quintana Roo* State; *Swietenia macrophylla* King (*caoba*), *Cedrela odorata* L. (*cedro)*, *Lysiloma latisiliquum* (L.) Benth. B. (*tzalam*), *Metopium brownei* (Jacq.) Urban L. & N (*chechem negro*), *Dendropanax arboreus* (L.) Decne & Planch. (*sacchacáh*), *Bursera simaruba* (L.) Sarg. B. (*chacáh rojo*), *Simarouba glauca* DC. C. (*negrito*) and *Manilkara zapota* (L.) Van Royen (*chicozapote*) are outstanding. These species are naturally distributed in populations in the whole state, since they are more abundant at the center and south.

Based upon the former, data were taken at the *Felipe Carrillo Puerto, X-Hazil, Chan Santa Cruz, Naranjal Poniente, Caobas* and *Bacalar ejidos*, which are located there (Figure 1).
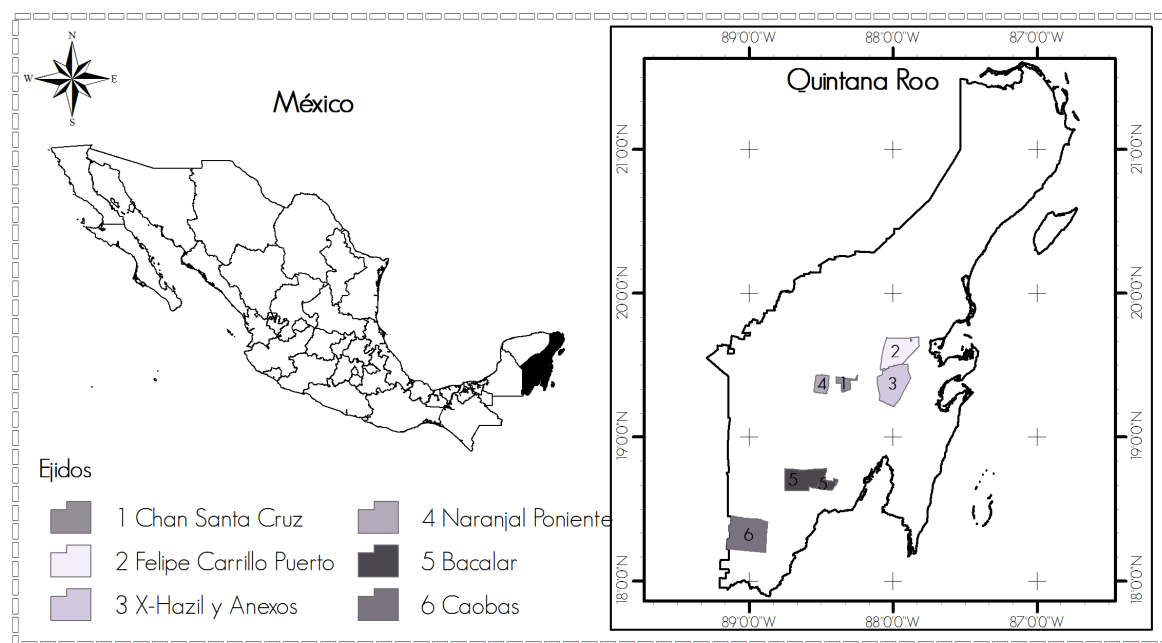

Figure 1. Geographic location of the study area for eight tropical forest species in *Quintana Roo*, Mexico.

A total of 1 169 pairs of *dt*, *d* and *h* data from trees of the eight species of commercial importance were collected by means of directed sampling and direct measurement for downed and indirect trees (relascopy) for standing trees (mahogany 137, red cedar 82, *chacah* 190, *chechem* 133, *ramón* 215, *sacchacáh* 128, *tzalam* 109 and *chicozapote* 175). All diametric categories and possible heights were included under different growing conditions.

For felled trees, the diameter with bark was measured with a Sweden Digitech Professional 80 cm Haglöf caliper at 0.30 m, 0.60 m, 0.90 m, 1.30 m and 2.5 m, then the diameter measurement was performed by sections at a variable length until reaching the tip and obtaining the total height. While for standing trees the diameter was directly measured at 0.30 m, 0.60 m, 0.90 m, 1.30 m and 2.5 m all with bark. With the *Parapente Nr.* 172305 Bitterlich telerelascope, diameters were taken at higher heights in sections of approximately 2.5 m in length, in tachymetric units and the height in percentage.

The volume of each section was calculated using the Smalian formula and the tip was cubed like a cone. The total volume of the tree resulted from the sum of the volume of each log and the volume of the tip, as indicated:

$$V_{trozas} = \left(\frac{g_0 + g_1}{2} \times L_1\right) + \left(\frac{g_1 + g_2}{2} \times L_2\right) + \text{·······} \left(\frac{g_{n-1} + g_n}{2} \times L_n\right) \quad and \quad V_{punta} = \left[\left(\frac{g_n \times L_n}{3}\right)\right]$$

Where:

V_{trozas} = Volume of the logs (m^3)

V_{Punta} = Volume of the tip (m^3)

g_o = Basimetric area of the greater diameter of the log (m^2)

g_1 = Basimetric area of the smaller diameter of the log (m^2)

g_n = Basimetric area of the diameter of the tip (m^2)

L = Length of the log (m)

Eleven linear and nonlinear models, which were proposed by Pompa *et al.* (2011), Quiñones *et al.* (2012), García-Cuevas *et al.* (2016) and others mentioned by Prodan *et al.* (1997) were tested (Table 1).

Atypical data were detected in the scatter diagram of the observed data and were removed.

A *PROC MODEL* was used for the fit with the method of greatest verisimilitude with complete information (FIML) to produce consistent estimators (SAS, 2015). The selection of the best model was based on the goodness of fit criteria: root mean square error (RCME), level of significance of the estimators (*Pr> ItI*), adjusted coefficient of determination (R^2_{adj}), and distribution of residuals against predicted. This analysis was useful to determine if the adjustments correspond to the tendency of the data (Huang, 2002; García-Cuevas *et al.,* 2016).

Table 1. Predictive models of normal diameter *(d),* total height *(h)* and stem volume *(v)* analyzed as a function of stump diameter (*dt*) for eight tropical forest species of *Quintana Roo*.

Ratio	Model	Identifier
d-dt	$d = \beta_0 + \beta_1 dt$	1
	$d = \beta_0 dt \left(\dfrac{1.3}{ht}\right)^{\beta_1}$	2
	$d = \beta_0 dt^{\beta_1}$	3
h-dt	$h = \beta_0 + \beta_1 dt$	4
	$h = \beta_0 + \beta_1 dt^{\beta_2}$	5
	$h = \beta_0 + \beta_1 dt + \beta_2 dt^2$	6
	$h = \beta_0 e^{\beta_1\left(\frac{1}{dt}\right)}$	7
	$h = 1.3 + \beta_0 e^{\beta_1\left(\frac{1}{dt}\right)}$	8
	$h = e^{\beta_0 + \beta_1 Ln\,(dt)}$	9
	$h = \beta_0 \left[1 - e^{\beta_1 dt}\right]^{\beta_2}$	10
v-dt	$v = \beta_0 dt^{\beta_1}$	11

The compliance with the regression assumptions was verified with the Shapiro-Wilk (SW) test for normality, with which we tested the hypotheses H_0: the observations have normal distribution; versus H_1: the observations have no normal distribution, rejecting the assumption of normal distribution ($p < 0.05$) (Balzarini *et al.,* 2008) and graphically for the homoscedasticity of residuals (SAS, 2015).

In the adjustments it is common to find problems of heteroskedasticity, therefore, a function that weights the residual variance (Residual / ((x) φ) 0.5) was included (Crecente *et al.,* 2009) by means of an exponential function according to the methodology suggested by Harvey (1976), where x is the form of the variable used and φ is derived from the linear regression of the natural logarithm (ln) of the residuals of the dependent variable as a function of the ln of x.

The equations of the best fit do not always estimate the real values with greater precision, so it must be taken into account that the regression analysis aims to develop the model that describes the population as a whole with greater fidelity (Hair *et al.*, 1999). Therefore, the use of a theoretical measure to evaluate the regression with respect to the difference between the effective dependent variable and its predictive value (error or bias) is important and is frequently used in forest models (Gadow and Hui, 1999; Castedo and Álvarez, 2000; Diéguez *et al.,* 2003; Corral *et al.,* 2007).

For the accuracy of the predictions, the average bias ($\overline{E}$) was estimated, which indicates the individual deviation of the model with respect to the observed values (Diéguez *et al.,* 2003) and. the aggregate difference (*DA* %), which indicates the deviation for the entire sample; the root of the mean error square (*RCME*); the adjusted coefficient of determination (R^2_{adj}), which reflects the total variability that is explained by the model and that take into account the total number of estimated parameters (Diéguez *et al.*, 2003; Barrio *et al.*, 2004; Trincado and Leal, 2006). One model will be better than another if it has a higher value of $\overline{E}$, RCME and a larger value of R^2_{adj}.

Results

Tables 2, 3 and 4 combine the results obtained for the best fitted equations; only in the total height of *Chacáh* are two equations exhibited, since equal results were obtained in the criteria of goodness of fit.

Analysis for *d-dt*

For the eight species, the dispersion of observed data of *d*, *h* and *v* as a function of *dt* (Figure 2) was plotted. A linear trend was obtained for the stump diameter-normal diameter ratio.

The estimation of the parameters of the best fitted equations as well as their goodness of fit criteria for each species are shown in Table 2. A better fit was calculated with model 2 from the analyzed models, which allowed to predict the normal diameter as a function of the diameter of the stump with greater accuracy.
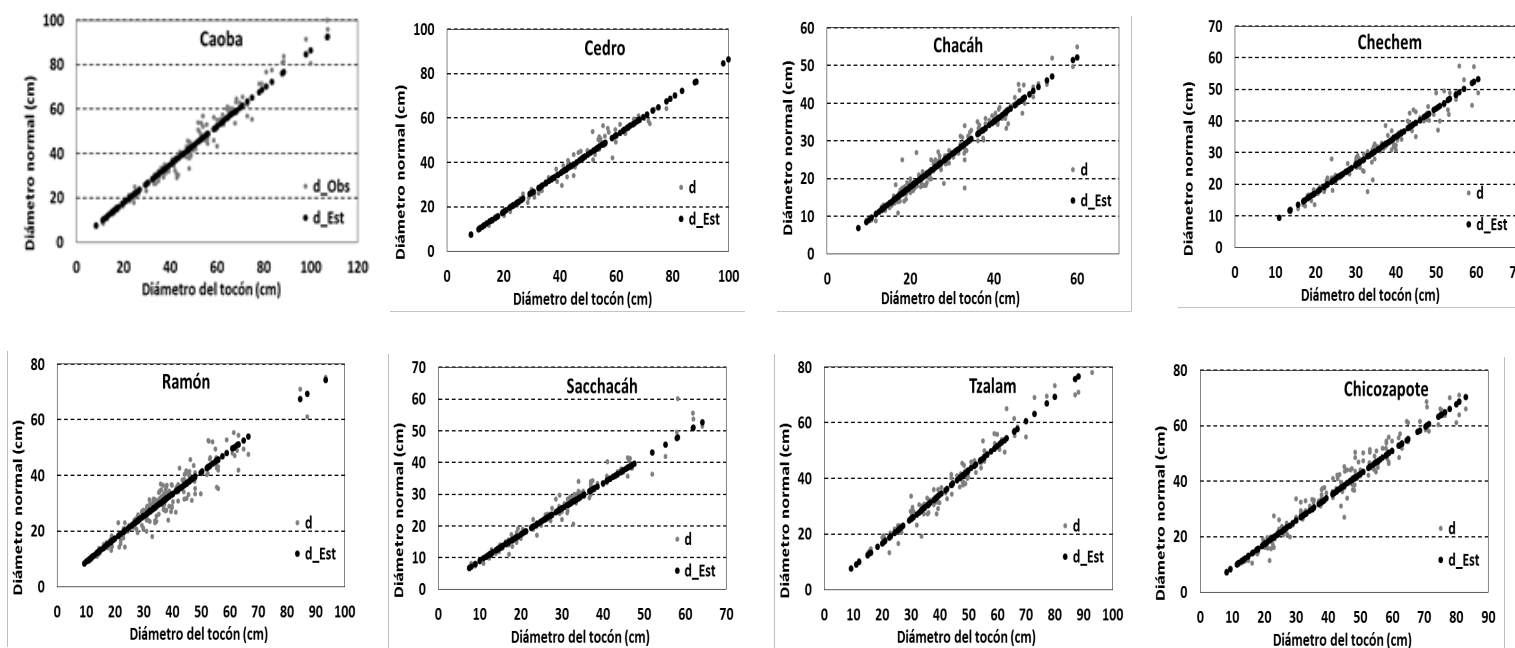
Caoba = Mahogany; *Cedro* = Cedar; *Diametro del tocón* = Stump diameter; Diámtreo normal = Normal diameter.

Figure 2. Observed and predicted data dispersion of the stump diameter-normal diameter for eight tropical forest species of *Quintana Roo*.

Model 1 also shows satisfactory fit, but for *Chacáh, Chechem, Sacchacáh, Tzalam* and *Chicozapote,* parameter β_0 was not significant, and thus it is not advisable.

For Model 2, the root mean square error (RMSE) (RCME for its acronym in Spanish) was reduced and the parameters of the equations are significant, and therefore it is inferred that they are valid to predict *d* from *dt* (Table 2).

Table 2. Summary of the best models to predict normal diameter from the stump diameter for eight tropical forest species of *Quintana Roo*.

| Species	Model	Gl	Estimator	Parameter	Pr>ItI	RCME	R^2_{adj}	SW	Pr<W	$\bar{E}$	DA (%)
Mahogany	2	137	β_0	0.211622	<0.0001	3.39	0.972	0.95	0.0001	0.05	0.12
			β_1	0.986669	<0.0001						
Cedar	2	82	β_0	0.299938	<0.0001	6.53	0.956	0.86	<0.0001	-1.00	-2.5
			β_1	0.905071	<0.0001						
Chacáh	2	190	β_0	0.221202	<0.0001	2.10	0.954	0.94	<0.0001	-0.04	-0.15
			β_1	0.976272	<0.0001						
Chechem	2	133	β_0	0.189947	<0.0001	2.47	0.949	0.97	0.0381	-0.15	-0.49
			β_1	1.017396	<0.0001						
Ramón	2	215	β_0	0.231697	<0.0001	3.73	0.932	0.98	0.1636	-0.16	-0.53
			β_1	0.948690	<0.0001						
Sacchacáh	2	152	β_0	0.22960	<0.0001	3.29	0.929	0.72	<0.0001	0.27	1.13
			β_1	0.95359	<0.0001						
Tzalam	2	107	β_0	0.178611	<0.0001	3.67	0.933	0.93	<0.0001	0.05	0.14
			β_1	1.027608	<0.0001						
Chicozapote	2	175	β_0	0.217831	<0.0001	3.33	0.957	0.98	0.7301	0.66	1.83
			β_1	0.977982	<0.0001						

GL = Degrees of freedom; Pr>ItI = Level of significance for the estimated parameters; RMCE = Root mean square error; R^2_{adj} = Adjusted coefficient of determination; DW = Durbin-Watson indicator; SW = Shapiro Wilk test; Pr<W = Level of significance for the Shapiro Wilk test; $\bar{E}$ = Bias or mean difference; DA % = Aggregate difference.

Another important criterion for checking the goodness of fit of the models is the value of the adjusted coefficient of determination (R^2_{adj}). In this case, the highest values obtained are for model 2, which in all cases explains above 92 % the variation of the data (Table 2). Similar results were reported by Pompa *et al.* (2011) with the same model, with values of 0.96 for *P. durangensis.*

The graphical analysis of residuals for model 2 (Figure 3) does not present systematic trends indicating heterogeneity of variances (heteroskedasticity).

In order to verify compliance with the assumptions of the regression, it is inferred that there are normal errors in model 2, because the values of the Shapiro-Wilk test (SW: Normal) are close to 1 (Velazco *et al.,* 2006). As there are sufficiently large samples, according to the central limit theorem, these samples tend to approximate to normality (Martínez-González *et al.,* 2007).
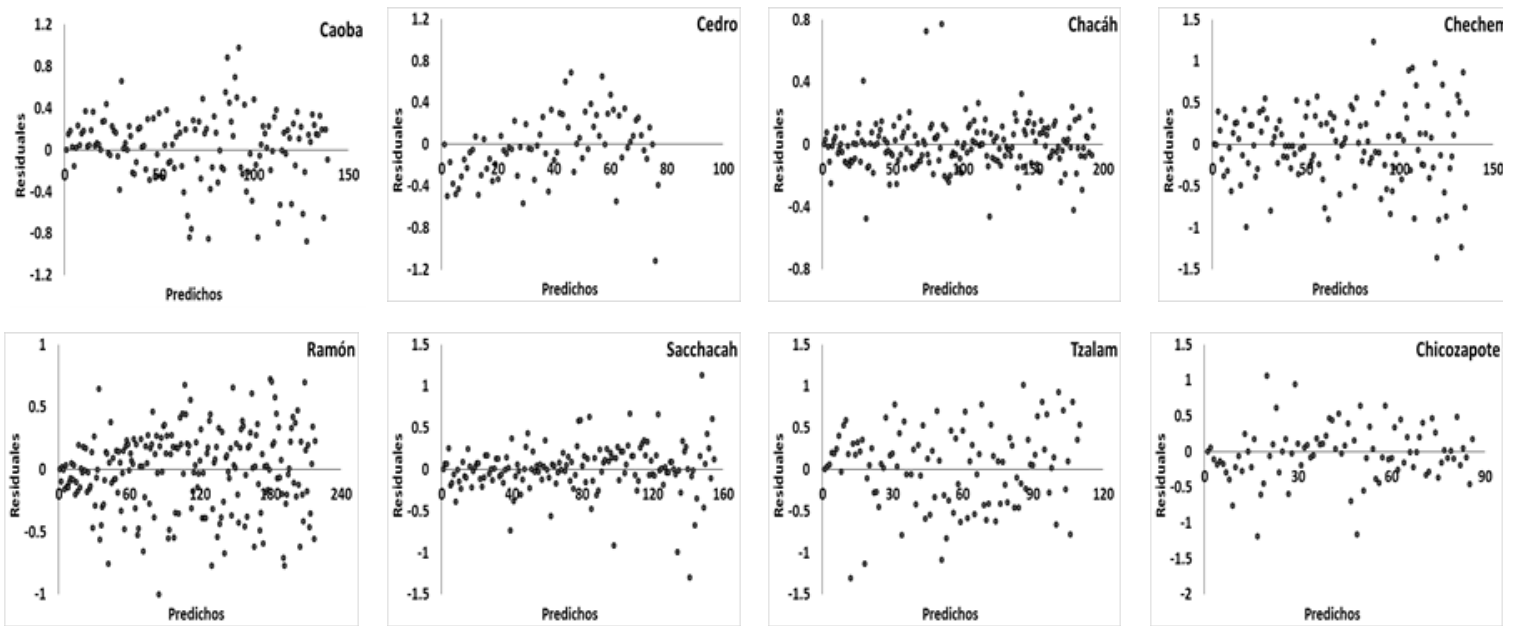
Residuales = Residuals; *Predichos* = Predicted

Figure 3. Residual dispersion of model 2 to predict normal diameter as a function of stump diameter for eight tropical forest species of *Quintana Roo*.

In regard to precision measurements, high predictive capacity is observed according to the small mean root mean square error and mean bias values, and a high R^2_{adj} value (Table 2). Negative biases indicate in how many units the prediction is overestimated at individual tree level and positive biases, underestimation. This is above that obtained by Pompa *et al*. (2011) with RMSE values greater than 5.7 and greater than 2.39 for *P. durangensis.*

The graphical analysis of predicted values *vs* observed data shows that model 2 predicts with high accuracy the normal diameter as a function of the stump diameter for the eight species (Figure 2).

Analysis for *h-dt*

The trend of the data is concave and asymptotic for total stump-height diameter, except *Sacchacáh* where it is observed rather linear (Figure 4).

Table 3 shows the estimation of the parameters of the best adjusted models, as well as their goodness of fit criteria. In order to estimate height, five models were fitted, which yielded satisfactory results for Mahogany (3), Cedar (7), *Chacah* (3 and 9), *Chechem* (10), Ramón (6), *Sacchacáh* (3), *Tzalam* (7) and *Chicozapote* (3).
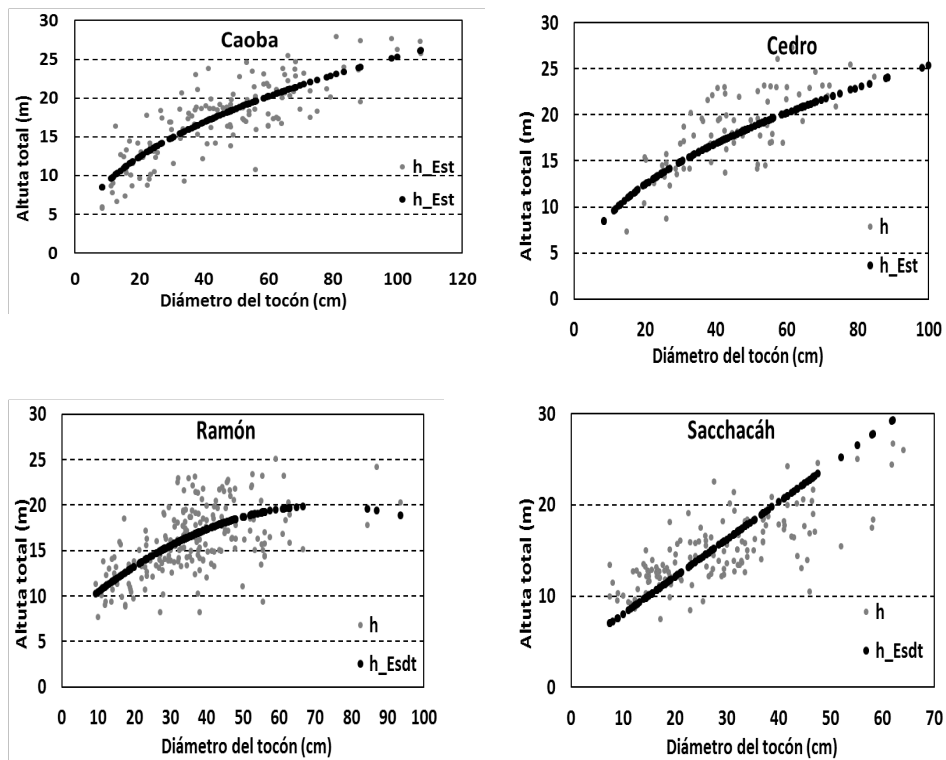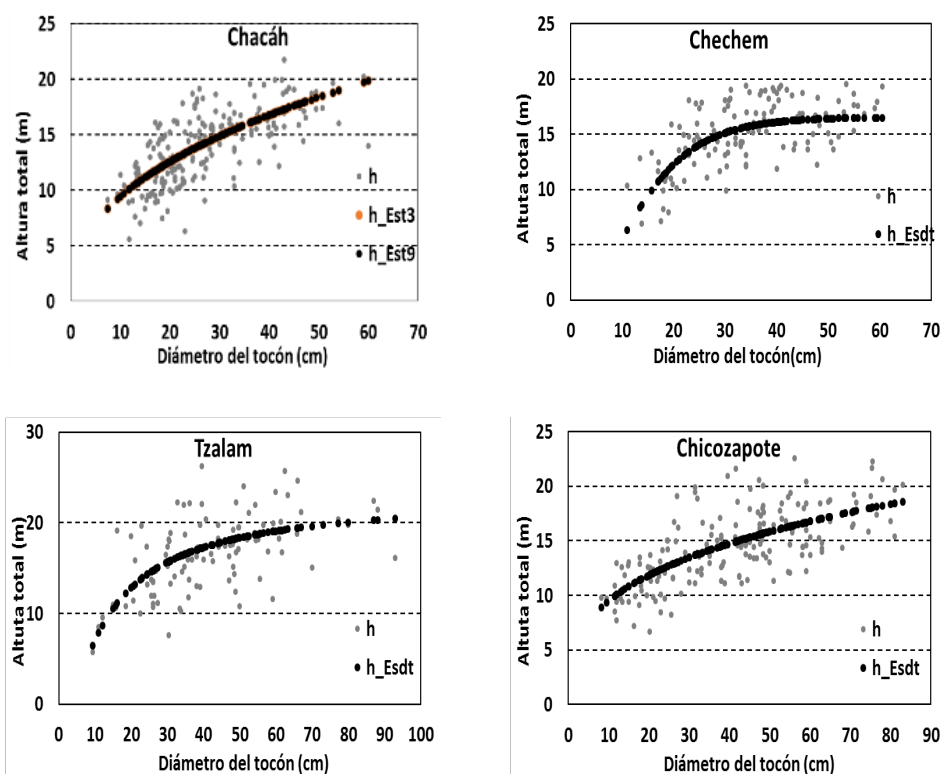
Diámetro normal = Normal diameter; *Diámetro del tocón* = Stump diameter =;

Altura total = Total height.

Figure 4. Observed and predicted data dispersion of the stump diameter-total height for eight tropical forest species of *Quintana Roo*.

The coefficients of the equations had a high level of significance, so it is inferred that the equations are valid to predict total height as a function of stump diameter.

The value of the adjusted determination coefficients (R^2_{adj}) for Mahogany, Cedar, *Chacáh* and *Sacchacáh* explain between 52 and 68 % of the variation of the data and for the other species only between 37 and 45 %.

Total height as a function of stump diameter is difficult to model, as described by Diéguez *et al.* (2003), who faced limitations to adjust equations in *Pinus pinaster* Aiton, *P. radiata* D. Don and *P. sylvestris* L. in Galicia, Spain. In Mexico, Quiñonez *et al.* (2012) also had problems adjusting equations in *P. arizonica, P. ayacahuite, P. durangensis, P. leiophylla, P. teocote* and *Quercus sideroxyla* in *Durango*. For them

the best model was the linear one, but with R^2_{adj} between 0.47 and 0.77, residue distributions showing heteroscedasticity, overestimation in the first height categories and one of the predicted values in some species.

Table 3. Summary of the best models to predict total height from the stump diameter for eight tropical forest species of Quintana Roo.

Species	Model	GI	Estimator	Parameter	Pr>ItI	RCME	R^2_{adj}	SW	Pr<W	$\bar{E}$	DA (%)
Mahogany	3	134	β1	3.294402	<0.0001	2.77	0.681	0.98	0.7090	-0.02	-0.13
			β2	0.443051	<0.0001						
Cedar	7	74	β1	28.41974	<0.0001	2.73	0.544	0.97	0.3774	0.02	0.10
			β2	-17.7005	<0.0001						
Chacáh	3	185	β1	3.625767	<0.0001	2.20	0.527	0.98	0.1117	-0.05	-0.39
			β2	0.415245	<0.0001						
Chacáh	9	185	β1	1.288095	<0.0001	2.20		0.98	0.1117	-0.05	-0.39
			β2	0.415241	<0.0001						
Chechem	10	123	β1	16.54043	<0.0001	2.18	0.424	0.98	0.3065	0.25	1.65
			β2	0.116689	0.0007						
			B3	2.954937	0.0173						
Ramón	6	210	β1	7.175811	<0.0001	3.00	0.395	0.98	0.3594	-0.01	-0.06
			β2	0.351123	<0.0001						
			B3	-0.00242	<0.0001						
Sacchacáh	3	125	β1	3.923006	<0.0001	2.40	0.636	0.97	0.2142	-0.55	-3.47
			β2	0.409593	<0.0001						
Tzalam	7	101	β1	4.109404	<0.0001	3.25	0.378	0.97	0.2365	-0.12	-0.72
			β2	0.382545	<0.0001						
Chicozapote	3	168	β1	4.582524	<0.0001	2.47	0.457	0.97	0.0140	-0.001	-0.006
			β2	0.316893	<0.0001						

GL = Degrees of freedom; Pr>ItI = Level of significance for the estimated parameters; RMCE = Root mean square error; R^2_{adj} = Adjusted coefficient of determination; DW = Durbin-Watson indicator; SW = Shapiro Wilk test; Pr<W = Level of significance for the Shapiro Wilk test; $\bar{E}$ = Bias or mean difference; DA % = Aggregate difference.

The graphical analysis of the residuals for the models (Figure 5) does not present systematic tendencies that indicate heteroscedasticity.

There is normality of errors in the Shapiro-Wilk (SW: Normal) test for C*hicozapote* because their values are close to 1 and with a high reliability level (Pr <DW). In Mahogany, Cedar, *Chacah, Chechem, Ramón, Sacchacáh* and *Tzalam*, reliability is not significant, but there is a sufficiently large sample and according to the central limit theorem, these samples tend to approximate to normality (Martínez-González *et al.,* 2007).

In regard to the accuracy of the predictions, it is observed that there is good predictive capacity according to the small values of the root mean square error, bias, aggregate deviation and greater R^2_{adj} (Table 3).

The graphical analysis of the predicted values *vs*. the observed data shows the fidelity with which the generated equations predict the total height as a function of the diameter of the stump (Figure 4).
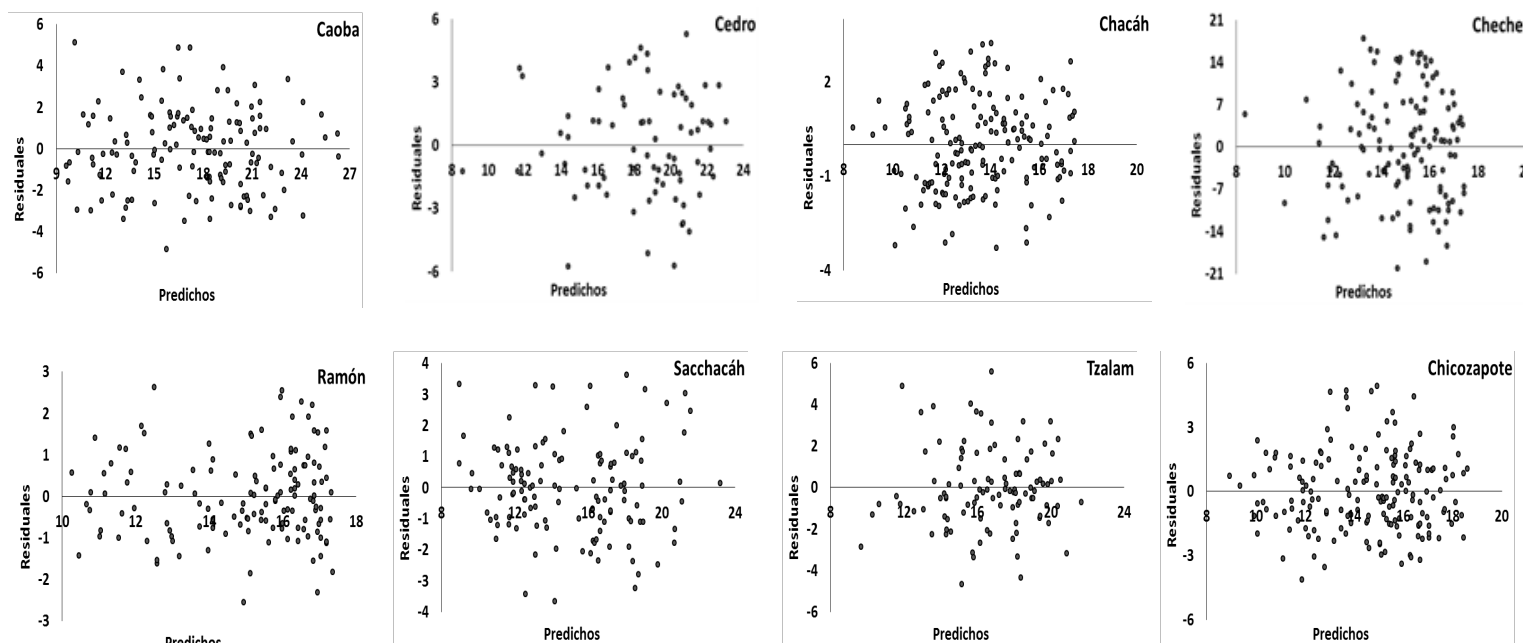

Residuales = Residuals; *Predichos* = Predicted

Figure 5. Residual dispersion of model 2 to predict total height as a function of stump diameter for eight tropical forest species of *Quintana Roo*.

Anaysis for *v-dt*

The trend of the data is potential for stump-volume diameter, where all diametric classes for individual trees of the eight species are represented (Figure 6).
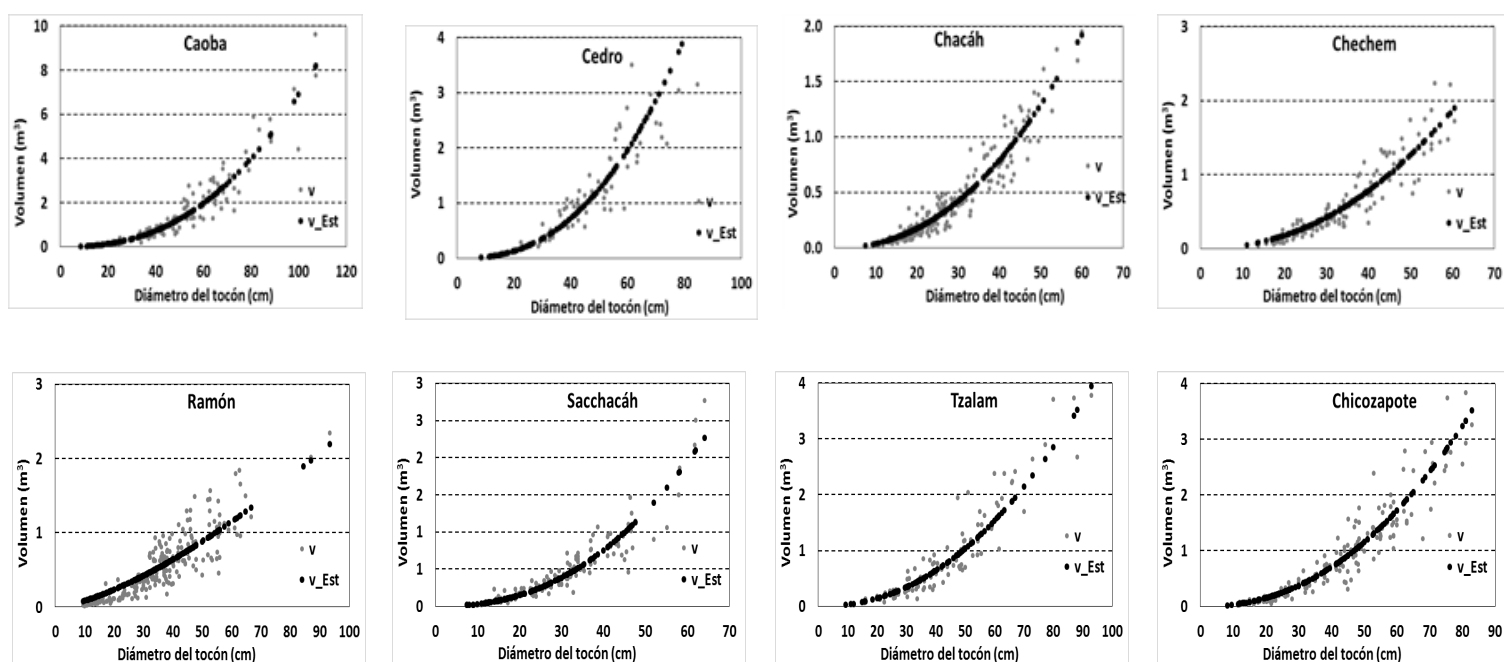
Volumen = Volume; *Diámetro del tocón* = Stump diameter =;

Caoba =Mahogany; *Cedro* = Cedro

Figure 6. Observed and predicted data dispersion of the stump diameter-volume for eight tropical forest species of *Quintana Roo*.

The allometric model described with high level of reliability the volume as a function of the diameter of the stump (Table 4). For the eight species, the coefficients of the equations were significant. In all cases the values of R^2_{adj} were high and explained

between 86 and 93 % of the variation of the observed data. The above agrees with what was obtained by Pompa *et al*. (2011) and Quiñonez *et al.* (2012), who determined for this relation coefficients of determination between 0.78 and 0.96 %.

Table 4. Summary of the best models to predict volume- stump diameter for eight tropical forest species of *Quintana Roo*.

Species	Model	Gl	Estimator	Parameter	Pr>ItI	RCME	R²$_{adj}$	SW	Pr<W	$\bar{E}$	DA (%)
Mahogany	3	139	β1	0.000082	0.0032	0.322	0.908	0.88	<0.0001	0.011	0.125
			β2	2.462668	<0.0001						
Cedar	3	79	β1	0.000769	<0.0001	0.543	0.937	0.85	<0.0001	-0.03	-2.87
			β2	1.905542	<0.0001						
Chacáh	3	187	β1	0.000239	<0.0001	0.115	0.910	0.96	0.0005	-0.002	-0.54
			β2	2.196484	<0.0001						
Chechem	3	134	β1	0.000292	0.0047	0.185	0.860	0.96	0.0024	-0.004	-0.572
			β2	2.139972	<0.0001						
Ramón	3	211	β1	0.003031	<0.0001	0.220	0.811	0.94	<0.0001	-0.011	-1.895
			β2	1.450779	<0.0001						
Sacchacáh	3	143	β1	0.000136	0.0004	0.140	0.911	0.91	<0.0001	0.003	0.63
			β2	2.336741	<0.0001						
Tzalam	3	103	β1	0.000229	0.0025	0.253	0.905	0.96	0.0181	0.028	3.128
			β2	2.152110	<0.0001						
Chicozapote	3	168	β1	0.000208	0.0009	0.276	0.901	0.89	<0.0001	-0.016	-0.243
			β2	2.203110	<0.0001						

GL = Degrees of freedom; Pr>ItI = Level of significance for the estimated parameters; RMCE = Root mean square error; R^2_{adj} = Adjusted coefficient of determination; DW = Durbin-Watson indicator; SW = Shapiro Wilk test; Pr<W =

Level of significance for the Shapiro Wilk test; $\bar{E}$ = Bias or mean difference; DA % = Aggregate difference.

Graphical analyzes of residuals do not present systematic trends indicating heterogeneity of variances (Figure 7).
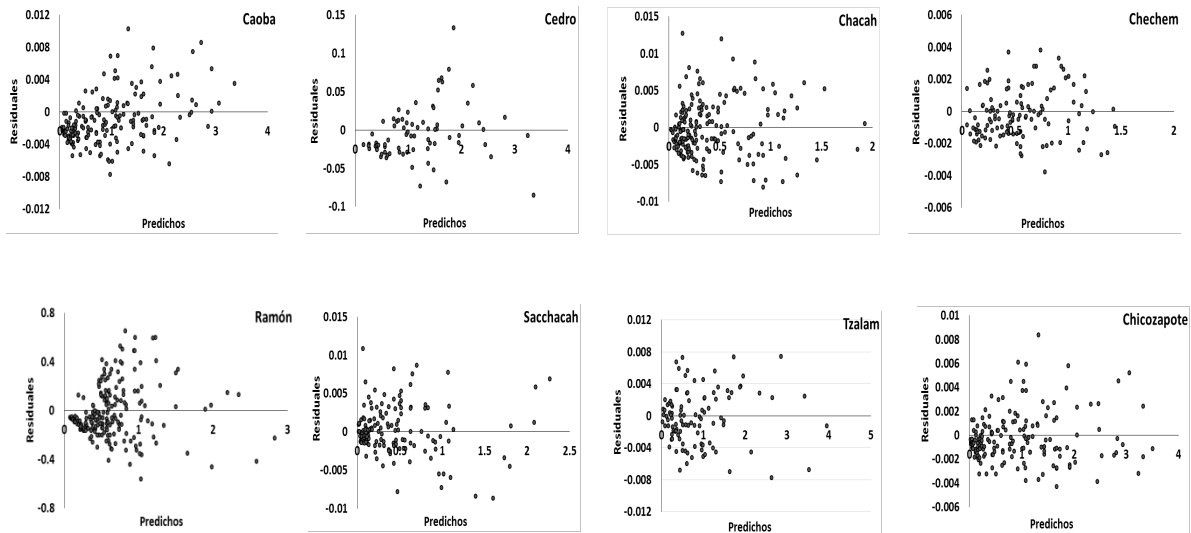
Caoba = Mahogany; *Cedro* = Cedro; *Residuales* = Residuals; *Predichos* = Predicted

Figure 7. Residual dispersion of model 2 to predict volume as a function of stump diameter for eight tropical forest species of *Quintana Roo*.

It is assumed that there are normal errors in all cases, because the values of the Shapiro-Wilk (W: Normal) test are close to 1 and with a high level of reliability (Pr <DW). In addition, the central limit theorem is satisfied for large samples, since these samples tend to approximate to normality (Martínez-González *et al.,* 2007).

The fitted equations have high predictive capacity according to the small root values of mean square error, bias, aggregate deviation and R^2_{adj} (Table 4).

Conclusions

Equations that allow to estimate normal diameter of felled trees from variables such as stump diameter and the height of the stump and for height and volume from stump diameter were obtained. The equations are reliable, they are highly accurate and practical, since the elements that must be included in them are variables easy to measure at the field.

Acknowledgements

Conflict of interests

The authors declare no conflict of interests.

Contribution by author

Xavier García Cuevas: data analysis, writing and correction of the document; Jonathan Hernández Ramos: field data collection and their analysis, writing and review of the document; Adrián Hernández Ramos: field data collection and review of the document; Gerónimo Quiñonez Barraza: data analysis and review of the document; Juan Carlos Tamarit Urías: data analysis and review of the document; Guadalupe Geraldine García-Espinoza: review of the document.