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Article

Ecuaciones alométricas para estimar biomasa y carbono aéreos de *Cedrela odorata* L. en plantaciones forestales

Allometric equations for estimating biomass and aerial carbon from *Cedrela odorata* L. in forest plantations

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Resumen

A partir de 27 árboles de tres plantaciones forestales de *Cedrela odorata* ubicadas en la región costera de Jalisco y Colima, se generaron ecuaciones alométricas para estimar la biomasa aérea y la concentración de carbono. Se seleccionaron los individuos mejor conformados, los cuales fueron cortados y medidos en campo, además se obtuvo el peso húmedo total del árbol por secciones. Para calcular la biomasa aérea y el carbono de los árboles, de cada sección (fuste, ramas y follaje) se tomaron muestras de madera y hojas, las cuales se llevaron a laboratorio para determinar su peso seco y concentración de carbono. Los datos del análisis de las muestras se extrapolaron a la sección y componente estructural correspondiente; mediante la adición de los valores resultantes, se estimó la concentración total de biomasa y carbono por individuo. Se probaron varios modelos, pero al final se ajustaron al modelo potencial: $Y=b\cdot X^k$, donde *Y* (*BS*: biomasa aérea en kg; *CC*: concentración de carbono en kg) es la variable respuesta y *X* (*DN*: diámetro normal en cm) la variable predictora. Las ecuaciones alométricas generadas fueron: $BS=0.00341\cdot DN^{3.38248}$, para estimar la biomasa aérea, y $CC=0.001562\cdot DN^{3.389696}$, para la concentración de carbono; ambas con un coeficiente de determinación ajustado R^2_a=0.978. Adicionalmente, para cada una de ellas, se realizaron las pruebas de normalidad, heterocedasticidad e independencia, cuyos resultados validan y garantizan la confiabilidad de los modelos obtenidos. Los resultados sugieren que las ecuaciones generadas permiten estimar la biomasa aérea y la concentración de carbono con base en el diámetro normal.

Palabras clave: Cedro, diámetro normal, heterocedasticidad, modelo potencial, plantaciones forestales, peso seco.

Abstract

Several allometric equations were generated for biomass and carbon content for *Cedrela odorata* trees. Twenty-seven trees were selected from tree different forest plantations in the states of *Jalisco* and *Colima*. The best trees were carefully chosen for felling, partitioning, and measuring in the field. Samples from the stem, branches and foliage were collected and sent to the laboratory in order to estimate their biomass and carbon content. The results from each sample were used to the different sections of the tree. Some models were tested, and the final potential model used was $Y=b\cdot x^k$; the allometric biomass equation is $AB=0.00341\cdot ND^{3.38248}$, and for carbon content is $CC=0.001562\cdot DN^{3.389696}$; where: *AB* is the aboveground biomass (kg); and *CC* is the aboveground carbon content (kg), *ND* is the normal diameter (cm). Both equations exhibited a good fit with an R^2 of 0.978, and the tests of normality, heteroscedasticity and independence, show good confidence and guarantee of the models developed. The results suggest that the equations generated allow estimating the aerial biomass and the carbon concentration based on the normal diameter.

Key words: Cedar, normal diameter, heterocedasticity, potential model, forest plantations, dry weight.

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Introduction

Greenhouse gases (GHG), such as carbon dioxide (CO_2), are the main anthropogenic GHG affecting the Earth's radiative balance. The most important source of CO_2 emissions is the combustion of fossil fuels; the second most important source includes deforestation and degradation of forest ecosystems (IPCC, 2007). In order to reverse the CO_2 concentration process, forest plantations are an alternative for carbon fixation, since they are ecosystems whose management is oriented to maximize the volume of wood per unit area, which gives them a high carbon storage capacity (González *et al.,* 2019). If, in addition, the wood is transformed into durable products, this fixed carbon will remain in the structures for a longer period (Ordóñez *et al.,* 2001).

Although several studies report different carbon concentrations according to tree species and tissue, varying in a range of 43 to 58 % of the biomass (IPCC, 2007), generally, the suggested factor is 0.50 (IPCC, 2007). However, for quantification purposes in C sequestration projects subject to financing, it is recommended to use specific carbon concentrations, for which it is necessary to have information differentiated by species and tree component (Gayoso and Guerra, 2005).

Allometric models are an indirect method of practical use for estimating the aboveground biomass of trees (Figueroa-Navarro *et al*., 2010); those based on destructive sampling also provide accurate estimates of biomass content (Gómez-Díaz *et al*., 2011). Therefore, they are a valuable tool for predicting the biomass and carbon of various tree species (Návar, 2010). Although biomass equations have been developed for tropical forests, temperate forests and some semi-arid vegetation types, the following equations are available (Návar *et al*., 2001; Rojas-García *et al*., 2015). In Mexico, there is very little information on the estimation of biomass in forest plantations.

Based on the above, the general objective of the present study was to generate allometric models of practical utility and statistically valid reliability, which allow estimating, within the recommended scope of application, both the amount of aboveground biomass and the capacity to store carbon in trees of different *Cedrela odorata* L. tree diameters.

Materials and Methods

Study area

The study was carried out in three forest plantations of *Cedrela odorata* species (Figure 1): 1) Experimental Site *Costa de Jalisco La Huerta*, municipality, *Jalisco* (19°31'15" N and 104°32'00" W; 298 masl), with a predominance of medium-textured haplic Phaeozem soils, and the climate corresponds to the Aw_1(w) type with annual rainfall of 1 012 mm; 2) *El Molino* farm, *Casimiro Castillo* municipality, *Jalisco* (19º32'05'' N and 104º26'20" W; 412 masl); the soils are of the distric Cambisol type, with a medium texture; the climate is Aw_2(w) with an average annual rainfall of 1 496 mm; and 3) *Tecomán* Experimental Station, *Tecomán* municipality, *Colima* (18°58'01" N and 103°50'32" W; 60 masl); the soil is classified as a medium-textured salic Calcisol, and the prevalent climate is BS1(h')w(w), with 790 mm of mean annual precipitation (Ruiz *et al*., 2012; INEGI, 2016). The predominant natural vegetation type in the area of influence of the properties corresponds to medium subdeciduous forest (*VSa/SMS* and *VSA/SMS*, i.e. SDTF and MSDF secondary arboreal vegetation).

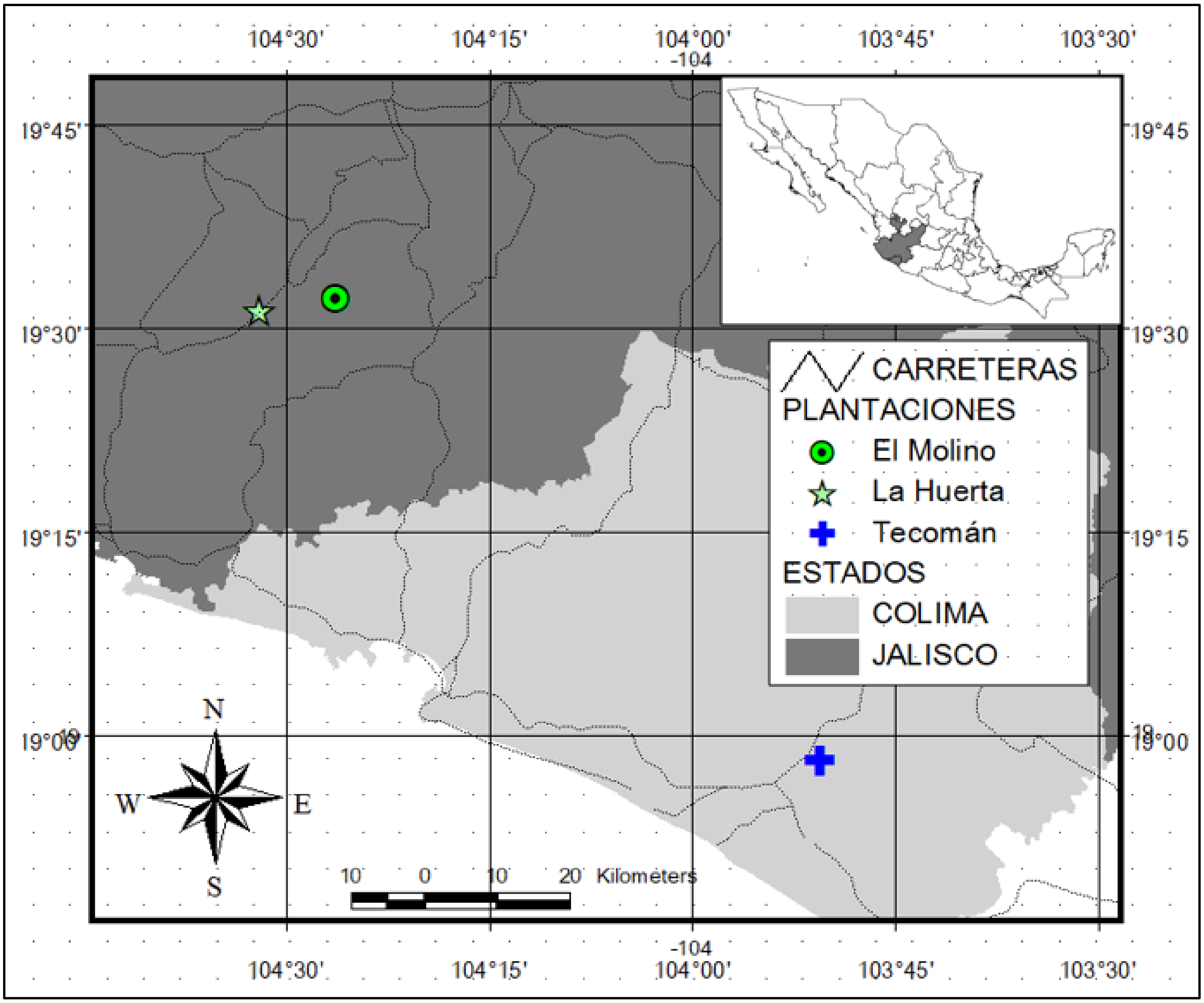


Figure 1. Location of the three *Cedrela odorata* L. forest plantations.

Sample tree selection

In the selection of the individuals that made up the sample, only those trees marked to be felled in the thinnings that are part of the management of the plantations were considered. The selective process began with the classification of the trees by 5 cm diameter classes. Since it was not a sampling exercise, healthy individuals without deformities were identified, from which 27 trees were selected (randomly), covering, proportionally, the range of diameter classes present in the three plantations (Ruiz-

Aquino *et al.*, 2014). With the trees still standing, the normal diameter (ND in cm) was measured with a diametric tape (Forestry Suppliers, 5 m). The individual trees were directionally felled with a chainsaw. In order to obtain its total height (TH, in m), the height of the stump was determined with a flexometer (Pretul, metalic metric tape, 5 m), and the tree was measured lengthwise with a longimeter (Truper®, 30 m fiberglass tape), from the base of the trunk to the apex of the crown, and the height of the clean trunk and its total length were also recorded.

Aerial biomass sampling

The methodology used to sample the aboveground biomass was that described by Díaz *et al.* and Figueroa-Navarro *et al.* (2010). In order to facilitate their use and management after felling, the aerial components of the tree (trunk, branches and foliage) were separated and sectioned as follows:1) logs 1.5 to 2.5 m long (base of stem and stump); 2) boles 1.0 to 1.25 m long (upper part of the stem and thick branches); 3) 1.0 m long firewood (thin branches and shaft tip); and 4) lower, middle and upper canopy foliage (leaves, fine twigs, flowers and fruits).

The wet weight of the structural components was recorded in the field and separately by component; for logs and noles, the weight of each section was obtained, from which a sample (5 cm wide slice) was taken; The firewood was arranged and weighed by loads, from each load two to six samples (10 cm long segments) were randomly extracted; while for the foliage, the collected material was weighed in three portions (lower, middle and upper part of the canopy), from which a sample (0.1 to 1.0 kg) was obtained at random. The sections were weighed with an electronic scale (Torrey CRS-500) with a capacity of 500 kg ± 0.1 kg; an electronic scale (Torrey PCR-20) with a capacity of 20 kg ± 0.01 kg was used to weigh the samples. The wet weight of the stump was estimated as follows: its volume was calculated with the cylinder formula, and a green density equal to that present in the first log was assumed.

Determination of aerial biomass

Once the wet weight was obtained in the field, the collected material was transferred to the laboratory for dehydration to constant weight in an electronic oven (Felisa, Fe-291ad); wood samples were dried at 70 °C (12-15 days), and foliage samples, at 35-40 °C (5 days); the dry weight was recorded with an accuracy of 1.0 g. The dry weight of each section was estimated by multiplying its wet weight by the factor resulting from the dry weight ratio: wet weight of the respective sample. The total aerial biomass of the tree and its structural components was calculated by adding the dry weight of its corresponding sections (Acosta-Mireles *et al*., 2002; Díaz *et al.,* 2007; Lim *et al.,* 2013; Cutini *et al.,* 2013; Rueda *et al.*, 2014).

Determination of carbon concentration

After the dry weight determination, component samples were taken from five randomly selected trees; a 100 g subsample was extracted from each one, ground and sent to the laboratory to determine their carbon concentration in a LECO TruSpec Micro equipment, which uses a combination of a continuous-flow carrier gas system and an infrared light system. With the results of the analysis, a biomass-to-carbon conversion factor (CF) was obtained for each component. The carbon concentration of the components was estimated as follows:

$$CCC_i = BC_i \cdot FC_i$$

Where:

CCC_i = Carbon concentration of component *i* (logs, logs, bolls, firewood and foliage; in kg)

BC_i = Biomass of component *i* (kg)

FC_i = Conversion factor of component *i*

The total carbon concentration of each tree is the sum of the carbon concentration of its components.

Model adjustment

Allometric models estimate biomass based exclusively on the normal diameter (Návar *et al*., 2004; Avendaño *et al*., 2009). However, several authors recommend including height, since it reduces the standard error, avoids overestimations and improves the fit of the models (Figueroa-Navarro *et al*., 2010; Ruiz *et al*., 2011; Rodríguez *et al.,* 2012)

Linear and nonlinear models cited in the specialized literature were tested to relate aboveground biomass (*BA*) to the variables normal diameter (*ND*) and total height (*TH*) or both ($ND \cdot TH$; $ND^2 \cdot TH$). According to the analysis performed, the best fit was obtained with the potential model expressed in its normal form as:

$$AB = \beta_0(ND)^{\beta_1}$$

Where:

AB = Aerial biomass (kg)

ND = Normal diameter (cm)

β_0 and β_1 = Estimated parameters of the function

This model is one of the most widely used to determine aboveground biomass (Acosta-Mireles *et al.,* 2002; Díaz *et al*., 2007; Gayoso *et al.*, 2002). This preference is because it expresses a proportionality of the relative increases between two tree dimensions and is broadly consistent for different growth forms (Gayoso *et al*., 2002).

In addition to obtaining the equation to determine the total aerial biomass of the tree, an equation for the biomass of its structural components was adjusted. In order to estimate the concentration of carbon in the aerial biomass of the tree using the same model, an equation was fitted that correlates the carbon concentration with the normal diameter of the tree.

The equations were fitted, statistically analyzed and diagnosed using the MODEL and NLIN procedures in SAS software (SAS Institute Inc., 2011). The criteria for rating the goodness-of-fit of the system that best explain the variability of the biomass data are based on a numerical and graphical analysis of the residuals (Gómez-Díaz *et al*, 2011). In the numerical case, statistics frequently used in biometrics were used, such as the adjusted coefficient of determination (R^2_a), the root mean square of the error (*RMSE*), the coefficient of variation (*CV*) and the significance of the parameters of each equation (Álvarez *et al.,* 2005; Rojo *et al.,* 2005). In addition, to validate the reliability of the results of the selected equation, the regression assumptions were verified analytically: normality (Shaphiro-Wilk, Kolmogorov-Smirnov, Cramer-von Mises and Anderson-Darling tests), independence (Durbin-Watson *d* test) and homoscedasticity (White and Breusch-Pagan tests) of the data (Fonseca *et al.,* 2011).

Results and Discussion

Estimation of tree biomass

The normal diameter of the sampled trees ranged from 4.0 to 28.0 cm; their aboveground biomass ranged from 2.42 to 275.53 kg, with a mean of 41.06 kg and standard deviation of 53.68 kg. The distribution of the aerial biomass of the tree is shown in Table 1; it can be seen that the highest average proportion corresponded to the trunk (logs and boles), with 71.37 %, followed by branches (firewood) and foliage with 21.96 and 6.67 %, respectively. The average percentage of logs (trunks), where the greatest proportion of biomass is concentrated, was similar to that cited for hardwood trees (49.1 %) (Soriano, 2014; Soriano-Luna *et al.,* 2015).

Table 1. Percentage of aboveground biomass by diameter class and component.

Aerial biomass (%)					
Diameter category (cm)	**Logs (1)**	**Boles (2)**	**Firewood (3)**	**Foliage (4)**	**Total timber (1+2+3)**
5	53.32	0.00	20.40	26.28	73.72
10	66.18	7.35	17.47	8.99	91.01
15	58.83	17.02	17.51	6.64	93.36
20	69.55	14.23	9.16	7.06	92.94
25	-	-	-	-	-
30	49.27	18.07	26.50	6.16	93.84
Weighted average	54.68 %	16.69 %	21.96 %	6.67 %	93.33 %

The equation determined to estimate the aerial biomass of *C. odorata* was expressed as follows:

$$AB = 0.00341 \cdot ND^{3.38248} \quad (1)$$

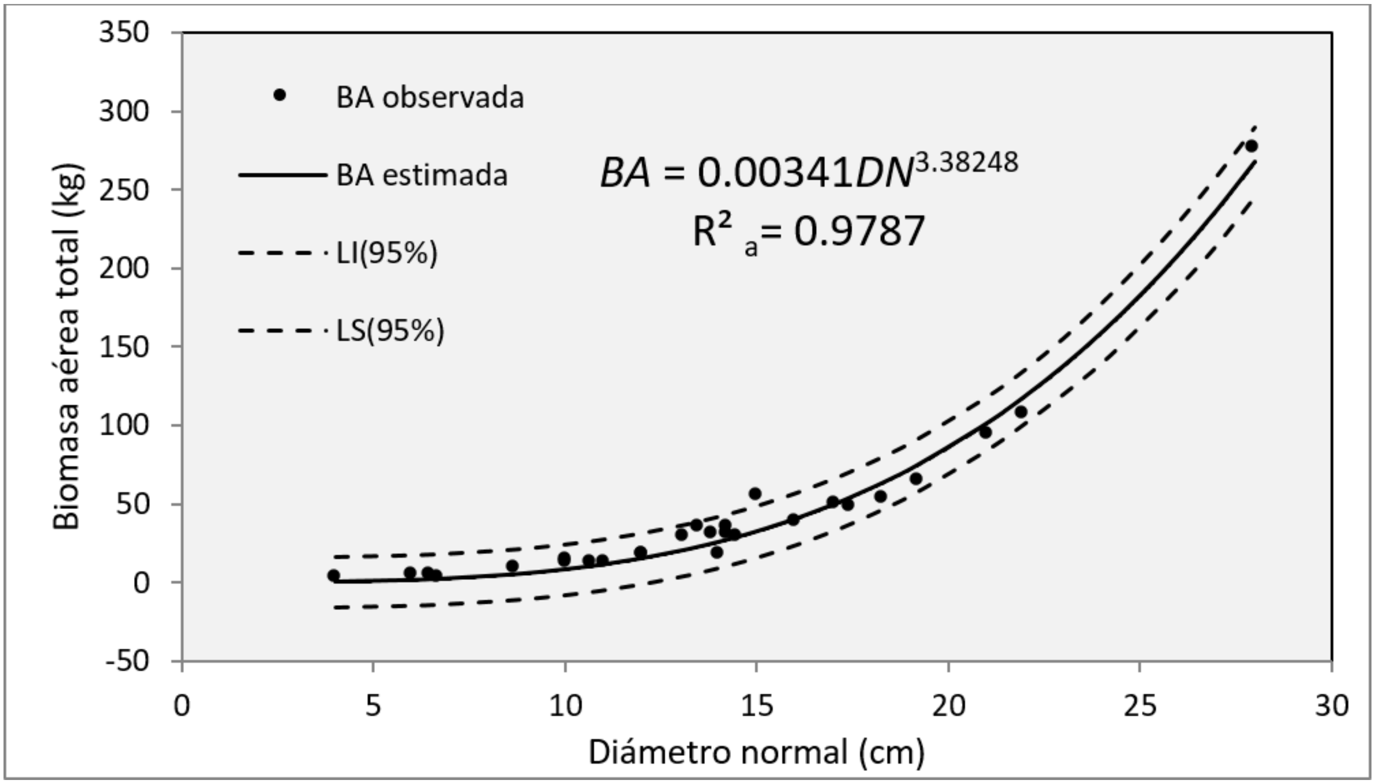
Where:

AB = Aerial biomass (kg)

ND = Normal diameter (cm)

The exponential trend of the equation coincides with what has been documented for *Pinus hartwegii* Lindl. (Carrillo *et al*., 2016). The equation analysis showed the following statistical indicators: adjusted coefficient of determination, R^2_a=0.9787; coefficient of variation, *CV*=390.449; and root mean square error, *RMSE*=7.487.

Figure 2 shows the scatter plot and the relationship between the variables *ND* and *AB* of the trees.



Biomasa aérea total = Total aerial biomass; *Diámetro normal* = Normal diameter.

Figure 2. Scatter plot and relationship between the normal diameter and the total aerial biomass of *Cedrela odorata* L. trees.

The different tests used for the analytical diagnosis of the model showed that the regression assumptions are verified, which validates the statistical analyses performed. Table 2 shows the values of the statistics.

Table 2. Statistics of the tests performed (95 % confidence interval).

Assumption	Test	Statistic		*p*-value	
Normality	Shapiro-Wilk	W	0.94268	Pr < W	0.1419
	Kolmogorov-Smirnov	D	0.15429	Pr > D	0.0958
	Cramer-von Mises	W^2	0.11319	Pr > W^2	0.0744
	Anderson-Darling	A^2	0.63713	Pr > A^2	0.0893
Homoscedasticity	White	nR^2aux	3.91	Pr > Chi^2	0.5630
	Breusch-Pagan	$0.5*SCEaux$	2.49	Pr > Chi^2	0.2885
Independence	Durbin-Watson *d* contrast	d	1.6996		

In reference to the assumption of normality, the four tests indicated that the residuals have a normal distribution (p-value > 0.05); for that of independence, the Durbin-Watson *d* test ($d_U < 1.6996 < 4\text{-}d_U$) showed that the residuals are not correlated; and for homoscedasticity, both the White test ($Chi^2 > 3.91$; p-value > 0.05) and the Breusch-Pagan test ($Chi^2 > 2.49$; p-value > 0.05) showed that there are no heteroscedasticity issues. The same model was fitted and an equation was generated for each component, whose parameters and regression estimators are summarized in Table 3.

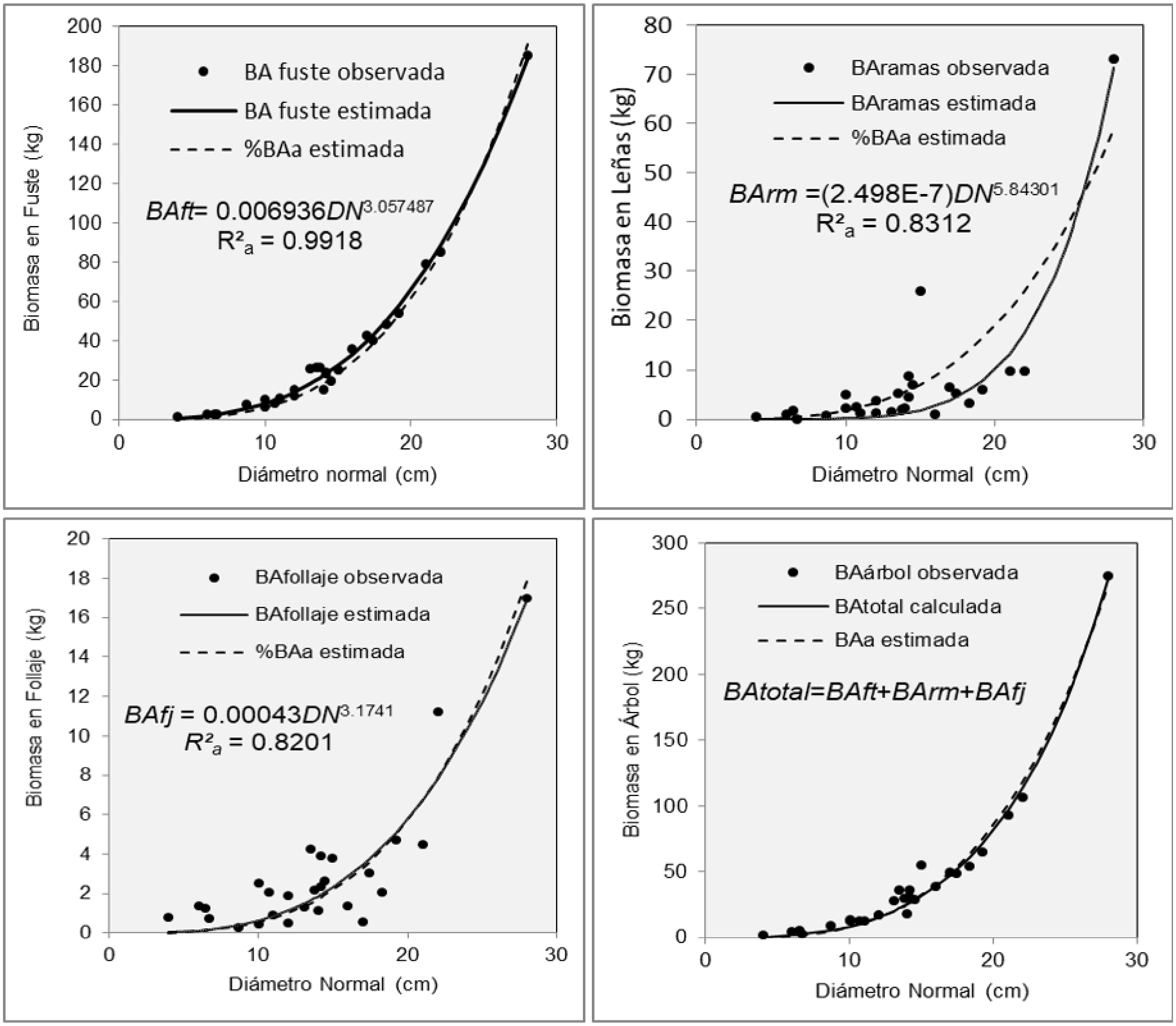
Table 3. Parameters and regression estimators of the fitted equations for biomass by structural component.

Parameter	Estimator	Standard error	*t value*	Pr > |*t*|	Root *MSE*	R^2_a	*W*	Pr < *W*
Stem (BAft)								
β_0	0.006936	0.00128	5.43	<0.0001	3.4223	0.9918	0.98	0.8686
β_1	3.057487	0.0584	52.34	<0.0001				
Branches (BArm)								
β_0	2.498E-7	6.265E-7	0.40	0.6935	5.8082	0.8312	0.72	<0.0001
β_1	5.843096	0.7601	7.69	<0.0001				
Foliage (BAfj)								
β_0	0.00043	0.000404	1.06	0.2977	1.5123	0.8201	0.98	0.8943
β_1	3.174131	0.2969	10.69	<0.0001				

$$AB_{total} = 0.006936(ND)^{3.057} + 0.000000249(ND)^{5.843} + 0.00043(ND)^{3.174}$$

AB_{total} = Total biomass estimated with model 1; *sAB*= Stem biomass; *bAB*= Branch biomass; *fAB*= Foliage biomass; AB_{total} = Total aerial biomass calculated through the sum of the estimated biomass for each of its components.

Figure 3 illustrates the scatter plots and the relationship of normal diameter with biomass by component of *Cedrela odorata*; the best fit of the model corresponded to the stem (biomass of logs and boles), with an R^2_a=0.9918. However, total biomass values were approximately one third of those reported for species such as *Alnus acuminata* Kunth (Díaz-Ríos *et al.*, 2016) and *Abies religiosa* (Kunth) Schltdl. et Cham. (Avendaño *et al*., 2009). On the other hand, the total biomass coincides with that cited for *Pinus hartwegii* (Carrillo *et al*., 2016).



Diámetro normal = Normal diameter; *Biomasa en fuste* = Stem biomass; *Biomasa en leñas* = Firewood biomass; *Biomasa en follaje* = Foliage biomass; *Biomasa en árbol* = Tree biomass.

BAtotal = Total biomass estimated with model 1; *BAft* = Stem biomass; *BArm* = Branch biomass; *BAfj* = Foliage biomass; *BAtotal* = Total aerial biomass calculated by means of the sum of the biomass estimated for each of its components.

Figure 3. Relationship between normal diameter and aerial biomass by structural component.

The graphs in Figure 3, plot not only the trend line obtained by fitting the potential model for the biomass of each component (solid line) but also the trend line resulting from the biomass partitioning (dotted line). The graph corresponding to the biomass of the stem, as in the case of the foliage, does not show significant differences in the behavior of both trends, while for the branches the differences are more evident, which could be due to the problems of normality in the data of this component.

Likewise, in the graph corresponding to total aboveground biomass, both the biomass estimated with equation 1 and that calculated by adding the biomass of its components show very similar trend lines. This reflects a biological logic in the distribution of the data, since the greatest proportion of the tree biomass is concentrated in the wood of the trunk and this exerts a greater influence on the model, both in the variability and in the normality of the data. Specifically, the trend defined for foliage is similar to that reported for *Abies religiosa*, although in this case, the model defined is polynomial (Flores-Nieves *et al*., 2011).

Regarding the relationship between stem biomass and normal diameter, the trend is similar to that presented by Flores-Nieves *et al.* (2011) and even fits an exponential model. However, it is important to consider that, in some cases, the biomass correlation is better defined by the tree height (Chou and Gutiérrez-Espeleta, 2013).

Estimation of carbon concentration

According to the analysis of the five sampled trees, whose carbon concentration by component is shown in Table 4, the biomass to carbon conversion factor (*CF*) is as follows= for the stem *sCF*=0.4688, branches *bCF*=0.4791, foliage *lCF*=0.4335 and for the tree *tCF*=0.4686. These values are slightly lower than those recorded for other species such as *Pinus hartwegii* Lindl. (Carrillo *et al*., 2016). However, they coincide with the carbon concentration of 7-year old pine and second vegetation forests (Figueroa-Navarro *et al*., 2005).

Table 4. Carbon concentration (%) of the analyzed samples.

Tree	Logs	Boles	Firewood	Foliage
3	45.22	48.83	48.29	-
7	45.96	43.39	48.67	41.46
9	49.18	48.93	48.59	44.24
12	46.58	46.65	47.08	42.30
15	47.34	-	46.93	45.40
Average	46.856	46.950	47.912	43.350
Standard deviation	1.52	2.60	0.84	1.80

In order to calculate more accurately the carbon concentration of the trees, the specific conversion factor for the biomass per component was used, and, with the sum of these values, the carbon concentration of each sampled tree was obtained. The average carbon distribution was 71.33 % for the stems, 22.49 % for the branches and 6.18 % for the foliage. By fitting the same model used for aerial biomass, the equation determined for estimating the carbon concentration of *C. odorata* was expressed as follows:

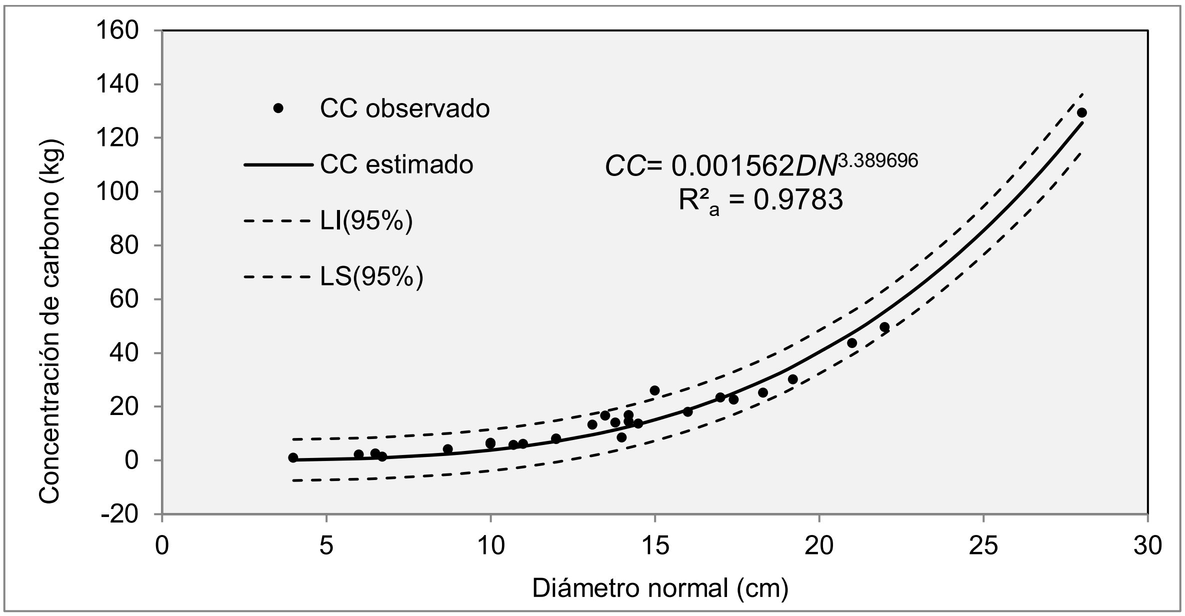
$$CC = 0.001562 \cdot ND^{3.389696} \quad (2)$$

Where:

CC = Carbon concentration (kg)

ND = Normal diameter (cm)

The equation analysis showed the following statistical indicators: adjusted coefficient of determination, R^2_a=0.9783; coefficient of variation, *CV*=391.503 and root mean square error, *RMSE*=3.7115. Figure 4 shows the scatter plot and the relationship between the variables *ND* and *CC* concentration of the trees.



Concentración de carbono = Carbon concentration; *Diámetro normal* = Normal diameter; *CC observado* = Observed CC; *CC estimado*= Estimated CC*.*

Figure 4. Scatter plot and relationship between normal diameter and carbon concentration in *Cedrela odorata* L. trees.

Conclusions

The concentration of carbon in the aerial biomass of *Cedrela odorata* trees is 46.86 % of the total carbon stored; 71.33 % is distributed in the trunk, 22.49 % in the branches and 6.18 % in the foliage.

When fitting the potential model $Y=b \cdot X^k$ to the biomass and carbon data of *C. odorata*, the equations generated to estimate aerial biomass and carbon concentration based on normal diameter show a very good fit, with coefficients of determination (R^2_a) above 0.978.

Based on the value of the statistical estimators, as well as on the normality, independence and heteroscedasticity tests, the determined equations are considered good and reliable for use with *C. odorata* under similar growth conditions.

The results of this study can be applied in the estimation of the biomass and the carbon potential of forest plantations to be established on specific areas at different scales.

Conflict of interests

The authors have stated that there are no competing interests.

Contribution by author

Juan de Dios Benavides Solorio: project coordination, data analysis, graphics and writing of the manuscript; Octavio Torres García: data collection in the field, graphs and tables and writing of the manuscript; José Germán Flores Garnica: data analysis and correction of the manuscript; Miguel Acosta Mireles: field data collection, methodology support and correction of the manuscript; Agustín Rueda Sánchez: data collection in the field, laboratory sample work and review of the manuscript.

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