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Article

Estimación del carbono almacenado en una plantación de *Tectona grandis* L. f. mediante ecuaciones alométricas

Stored carbon estimation of a *Tectona grandis* L. f. plantation using allometric equations

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Resumen

El bióxido de carbono (CO_2) es el principal gas de efecto invernadero (GEI) antropogénico de la atmósfera. El objetivo de la investigación que se describe a continuación consistió en estimar el carbono almacenado a partir de variables dasométricas y ecuaciones alométricas en una plantación de *Tectona grandis* en Michoacán, México. Para ello se ajustó un modelo matemático mediante procedimiento *Model* y algoritmo *Gauss-Newton*. La evaluación del modelo matemático se realizó en función de la suma de cuadrado del error (SCE), la raíz del error medio cuadrático (REMC) y R^2_{adj} además de la significancia de sus parámetros. Se verificó el cumplimiento de los supuestos de normalidad, homogeneidad de varianzas e independencia de la frecuencia de residuos. Los valores de los parámetros del modelo ajustado fueron SCE=0.0399, REMC=0.0179 y R^2_{adj}= 0.82. La prueba de *Shapiro-Wilk* (0.96), la de *White* (12.99) y la de *Durbin-Watson* (2.01) no violan los supuestos de la regresión y son los mejores para la estimación de la variable dependiente. La plantación de *T. grandis* presenta una densidad de 1 666 árboles ha^{-1}, 220.29 m^3 ha^{-1} de madera, densidad básica 0.59 g cm^3 y almacena 77.20 ton ha^{-1} de carbono a los 11 años de edad. La ecuación ajustada permite estimar de manera indirecta el carbono almacenado en los árboles, puede adecuarse para plantaciones bajo condiciones bioclimáticas similares, y es factible incorporarla a los sistemas de productividad para calcular el potencial de las plantaciones forestales comerciales como proveedoras de servicios ambientales a fin de mitigar las emisiones de CO_2.

Palabras clave: Bióxido de carbono, cambio climático, factor de expansión de biomasa, modelo alométrico, plantaciones forestales, *Tectona grandis* L. f.

Abstract

Carbon dioxide (CO_2) is the main anthropogenic greenhouse gas (GHG) in the atmosphere. The objective of the research described below was to estimate the carbon stored from mensuration variables and allometric equations in a *Tectona grandis* plantation in *Michoacán*, Mexico. Thus, a mathematical model was adjusted using the Model procedure and Gauss-Newton algorithm. The evaluation of the mathematical model was made from the sum of the square of the error (SCE), the root of the mean quadratic error (REMC) and R^2_{adj} in addition to the significance of its parameters. Compliance with the assumptions of normality, homogeneity of variances and independence of waste frequency was verified. The values of the parameters of the adjusted model were SCE=0.0399, REMC=0.0179 and R^2_{adj}=0.82. The Shapiro-Wilk test (0.96), White´s test (12.99) and the Durbin-Watson test (2.01) do not violate regression assumptions and are best for estimation of the dependent variable. The *T. grandis* plantation has a density of 1 666 trees ha^{-1}, 220.29 m^3 ha^{-1} of wood, basic density 0.59 g cm^3 and stores 77.20 ton ha^{-1} of carbon at 11 years old. The adjusted equation allows to estimate in an indirect way the carbon stored in the trees, it can be adjusted for plantations with similar bioclimatic conditions, in addition it is feasible to incorporate it to the productivity systems to evaluate the potential of the commercial forest plantations as environmental services in order to mitigate the CO_2 emissions.

Key words: Carbon dioxide, climate change, biomass expansion factor, allometric model, forest plantations, *Tectona grandis* L. f.

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Introduction

Carbon dioxide (CO_2) is the primary anthropogenic greenhouse gas (GHG) in the atmosphere; it contributes around 65 % to the radiative force produced by the GHGs of long permanence (difference between the insolation absorbed by the Earth and the energy radiated back to space (NOAA, 2016).

The preindustrial atmospheric CO_2 content was conserved below 280 ppm (NOAA, 2019) throughout the glacial and interglacial cycles, but rose to a global average of 409.95 ppm in August 2019. Atmospheric CO_2 added 145 % of the pre-industrial level in 2016 mainly from fossil fuel combustion emissions and cement fabrication (in 2015 the total CO_2 emissions were 9.9 ± 0.5 Pg C) (IPCC, 2015), deforestation and other land use changes (on average 1.0 ± 0.5 Pg C for the 2006–2015 period).

Of the total emissions caused by human activities during the 2006-2015 period, about 44 % were stored in the atmosphere, 26 % in the oceans and 30 % on earth (Le Quéré *et al*., 2016). One way to lessen its effects is to store it in biomass through photosynthesis (Ávila *et al*., 2001); the potential for carbon sequestration by plant communities varies considering the structure and constitution of each ecosystem (Gómez *et al.*, 2011).

Allometric biomass equations relate the individual measurement of biomass and its evaluation in the field based on inventory data (Picard *et al.*, 2012). Biomass is used to estimate the accumulated carbon of tree species, by multiplying the amount usable at a site by a coefficient that varies from 0.40 to 0.55. These factors are specified by different authors, among which Díaz *et al*. (2007), Jiménez *et al*. (2008), Kongsager *et al*. (2013); and Jaramillo and Correa (2015).

Some estimates show that by the end of this century, natural forests will be reduced by 30% and forest plantations will represent 20 % of the world's forest area (Brockerhoff *et al*., 2013). The absorption potential of the forest sector in Mexico has been considered at 58 million tons of carbon dioxide equivalent (t CO_2e) by 2020 and 96 million tons of CO_2e by 2030. Based on the above, it is estimated that Carbon sinks in the forest area by 2022 would be competent enough to neutralize emissions from other sectors in the country (Conafor, 2013).

Teak is a transcendental exotic forest species in Mexico (*Tectona grandis* L. f.), among other reasons, for its good acclimatization in various regions of the states of *Campeche, Chiapas, Tabasco, Veracruz, Michoacán* and *Nayarit* (Fierros, 2012). *T. grandis* plantations can be attractive activities for carbon fixation, as it is a fast growing species (Langenberger and Liu, 2013). There are not many case studies on the estimation of carbon stored for *T. grandis* in the plantations of Mexico, so it is unavoidable to develop research that gives successful results to landowners, as well as to investors interested in the species.

T. grandis is grown as exotic in many countries, but it is not invasive, as it does not affect local ecosystems; also, together with *Gmelina arborea* Roxb. and several species of pine, it grows in pure stands in natural forests. If it is cultivated through good forestry management practices, the threat of soil erosion is minimal (de Camino and Pierre, 2013). It is a preferred option for plantations because it is easy to spread, establish and manage; teak's reputation is due to its wood that is of excellent quality from its properties: strong, light, durable, dimensional stability; it does not corrode in contact with metals; good workability and hardness; resistance to termites, chemicals, fungi and weathering (Keogh, 2013).

Based on the aforementioned, the objective of the study was to estimate the carbon stored from mensuration variables and allometric equations in a plantation of *T. grandis* L. f. at 11 years from its establishment in *Nuevo Urecho, Michoacán, Mexico.*

Materials and Methods

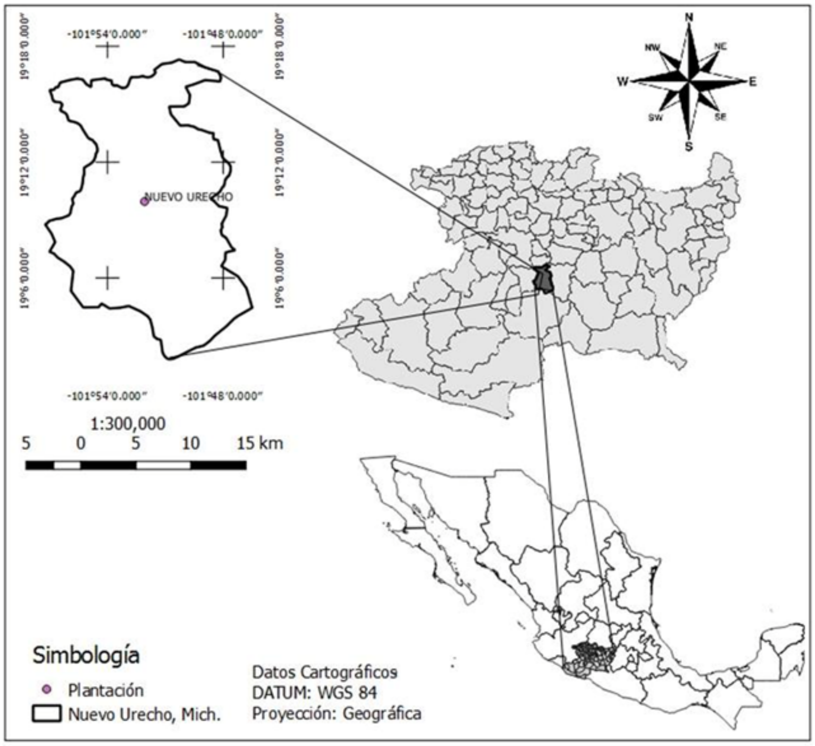
Study area

This research study was carried out in a commercial forest plantation of *T. grandis*, located in the *El Mirador* area, *Nuevo Urecho* municipality, *Michoacán* State, Mexico; it is part of the Transversal Neovolcanic Axis region in which the *El Tipítaro, Las Gallinas, Agua Fría* and *Las Cuevas* hills are part of it (INEGI, 2009). Its geographical delimitation is between 19°11´39.6" N and 101°51´53.3" W, at an average altitude of 617 m. Slope in the place is flat, from 1 % to 2 %. The plantation was. The trees are planted with a spacing of 2.0 × 3.0 m, which corresponds to a density of 1 666 ha^{-1} trees in a surface area of 6 ha.

The dominant soils are Vertisol (38.32 %), Luvisol (32.24 %), Leptosol (26.08 %), Pheaozem (2.84 %), Fluvisol (0.28 %) and Regosol (0.03 %). The climatic formula is Aw_o (w) warm subhumid with rains in summer, of medium humidity (91.16 %); average annual temperature of 20 °C to 28 °C and annual rainfall of 700 mm to 1 100 mm (INEGI, 2009).

Within the study area, the trees selected based on the methodology proposed by Segura and Andrade (2008), who indicate that the individuals to be measured must be "typical" of the species and site, under the assumption that trees match the shape and health of the shaft of the sampled population; the shape of the trees is often correlated with the size of the trees, so that the normal diameter and total height generally explain much of the variation in volume caused by it, as sated by Emanuelli and Milla (2014).

Some specimens were chosen without damage or defects, in order to include as many diametric and height classes as possible, as suggested by Barrios *et al.* (2014). Regarding the number of trees, the recommendation was followed by Louppe and Mille (2015) in the sense that 100 trees are measured in the case of a stand or several stands of recent planting on a restricted area (Figure 1).



Simbología = Symbology; *Datos cartográficos* = Cartographic data; *Proyección* = Projection.

Figure 1. Study area at *Nuevo Urecho* municipality, *Michoacán*.

Mensuration data

Data collection was done in 2014, when the plantation was 11 old. A selective sampling of trees with conditions and variations in their measurements was used for a good adjustment. In total, 128 trees were measured, which were indirectly taken data of diameter at 1.30 m ($d_{1.3}$) and total height (AT) with the Criterion RD 1000® dendrometer.

Estimation of carbon stored in trees

To estimate the carbon stored in the trees, a non-destructive sampling was carried out, using mensuration data (shaft diameter, total height, basal area and shaft volume) of *T. grandis* (Equation 1):

$$C_{stored}\,(tC/tree) = (Vcc * D * \, FEB) * ((1 + R) * FC) \qquad (1)$$

Where:

Vcc= Stem volume with bark (m^3)

D= Basic density (g cm^{-3})

FEB= Biomass Expansion Factor

1+R= Root biomass/ Total biomass relation factor

FC= Biomass (dry matter) to carbon (%) conversion factor

Log volume with bark (m^3). This component was calculated with the Meyer equation adjusted by Telles *et al*. (2018) for the *T. grandis* plantation established in *Nuevo Urecho Michoacán* (Equation 2):

$$V = \, 0.127677 + -0.018420. d + 0.000815. d^2 + 0.000374. d. H + \varepsilon \quad (2)$$

Where:

V= Log volume (m^3)

d= Normal diameter (cm)

H= Total height (m)

Basic density. For the *T. grandis* wood located in *Nuevo Urecho Michoacán*, the basic density is 0.59 g cm^3 (Telles *et al*., 2017).

Biomass expansion factor (FEB). In this research study, the FEB of 1.08 recorded for *T. grandis* by López *et al*. (2018) was used.

Root biomass / total biomass ratio factor (R/T). MacDicken (1997) recommends a value of 0.10, which was used by Fonseca *et al.* (2009) to estimate the biomass of native species in plantations and secondary forests in *Costa Rica*; Espíritu *et al.* (2016) used a value of 0.20 to determine the ratio of radical biomass / total biomass for different species in the *El Huayo arboretum, Loreto, Perú*. It was decided to use the value recommended by MacDicken (1997) as it is a conservative option.

Conversion factor (FC). Conversion factor from ton of biomass (dry matter) to ton of carbon (tC). It is the percentage of mass carbon of wood: 50 % carbon; 41 % oxygen; 6 % hydrogen; 1 % nitrogen and 2 % ash, so the amount of carbon per ton of biomass (dry matter) is close to 500 kg (50 %) (Norverto, 2006); Montero and Kanninen (2006) refer values of 41.6 and 49.6 % for *T. grandis*.

Model adjusment

The estimation of the parameters in the adjustment of the mathematical model was carried out with iterative methods (Draper and Smith, 2014), with the Model procedure and the Gauss-Newton algorithm of the statistical SAS package (Statistical Analysis System) 9.2® (Allison, 2010), using the method of ordinary least squares adjustment (MCO).

Model evaluation criteria

The assessment of the allometric equation was carried out from the goodness of fit, measured with the sum of squares for error (SCE), the root mean squared error (REMC) (Equation 3), the coefficient of determination adjusted by the number of model parameters (R^2_{adj}), and the significance of the parameters (Schlaegel, 1982; Parresol, 1999; Tedeschi, 2006):

$$REMC = \sqrt{\frac{\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2}{n-p}} \qquad (3)$$

Model validation

When the variances of the frequency of the residues are heterogeneous (heterocedasticity) or when the residuals are autocorrelated, the estimation of the regression coefficients by the method of ordinary least squares are adversely affected and the estimation of the standard error is biased (Da Cunha *et al*., 2009). For this reason, the validation of the mathematical equation chosen for the verification of the aforementioned assumptions, which indicates the quality of the prediction, is discussed.

To verify compliance with the regression assumptions, the normality, homogeneity and independence of the residuals were determined:

a) Normality of waste. The statistics of Shapiro-Wilk were calculated (Equation 4) (Da Cunha *et al*., 2009):

$$W_c = \frac{b^2}{\sum_{i=1}^{n}(X_i - \hat{y})^2} \qquad (4)$$

Where:

W_c = Shapiro-Wilk statistic

$b = \sum a_{i}{}_{i=1}^{n} [X_{(n-i+1)} - X_i]$, where a_i= Value of a tabulated coefficient for each sample size and the observation *i* position

$[X_{(n-i+1)} - X_i]$ = Succesive differences obtained from the substraction of the first value from the last one, the second from the penultimate, the third one from the antepenultimate and so forth until substracting the last from the first value

b) Homogeneity of waste variances; one of the transcendental assumptions towards the least squares of the usual regression is the homogeneity of variance (homocedasticity) (Emanuelli and Milla, 2014). The mathematical method to determine if there is homogeneity of variance of the residues was performed using the White test (De Arce and Mahía, 2009).

c) Independence of waste; it is expected that the "*d*" statistic (Equation 5), is approximately equal to 2, if the residuals are independent. In the inverse argument, if the residuals are positively correlated, they will tend to be close to 0 (zero), or close to 4, if the residuals are negatively correlated (Emanuelli and Milla, 2014). The value of "*d*" will be provided by:

$$d = \frac{\sum_{i=2}^{n}(E_i - E_{i-1})^2}{\sum_{i=1}^{n} E_i^2} \qquad (5)$$

Where:

d= Durbin-Watson's "*d*" statistic

n= Number of observations

E_i= Stocastic error =, y_i= $\hat{y}_i$

The distribution of the residuals was analyzed using the graphical method of the regression equation adjusted to estimate the carbon stored for *T. grandis* and to be able to observe the distribution of the residues (differences between observed value and predicted value), as recommended by Álvarez *et al*. (2003), mention that there is some deficiency of the adjusted model in this way.

Results and Discussion

Based on the forest inventory carried out in 2014, the plantation, consisting of 1 666 ha^{-1} trees of 11 years, grows in a surface area of 6 ha^{-1}; the average normal diameter of the trees is 16.55 cm, total height is 13.01 m; the basal area is 2.17 m^2 ha^{-1}. The log volume (220.29 m^3 ha^{-1}) was calculated with the Meyer equation (Telles *et al*., 2018), and does not include the volume of the branches, twigs and leaves.

The four parameter equation is presented, which takes as the adjustment variables to the total height (*h*), the normal diameter (*d*), density (*D*), biomass expansion factor (*BEF*), radical biomass / total biomass ratio (*1 + R*), conversion factor (*FC*), based on the indicators of goodness of fit (R^2 adjusted and REMC) and level of reliability, tests of normality of the residuals and the measures to estimate the predictive capacity of the model, the data set of 128 trees of *T. grandis*. The value of SCE (0.00399) gives an explicit expression of the estimated coefficients (Table 1).

Table 1. Values of the goodness of fit statistics of the evaluated equation in the stored carbon estimate in *Tectona grandis* L. f.

Model	R^2_{adj}	SCE	REMC	β_i	Estimated value	Standard error	Prob> T
$C_{stored}\,(t) = ((\beta_0 + \beta_1.d + \beta_2.d^2 + \beta_3.d.h.D.FEB).((1+R).FC)$	0.82	0.00399	0.017	0	0.364129	0.1526	0.0185
				1	-0.05252	0.0187	0.0057
				2	0.002326	0.000555	<0.0001
				3	0.001067	0.00019	<0.0001

R^2_{adj} = Adjusted coefficient of determination; SCE = Sum of square error; β_i = Estimated parameters; REMC = Root of the mean square of the error.

The model has an adjusted coefficient of determination of 0.82, which explains 82 % of the total variability in the dependent variable, with a *RECM* value = 0.0179, and a high significance in each of its parameters (Table 1); an absolute bias value = 0.0082 m^3 which indicates that there is the minimum deviation of the model with respect to the observed values, so it is considered appropriate to accurately predict the carbon stored as a function of the fusel volume (*Vcc*), density (*D*), biomass expansion factor (*FEB*), radical biomass-total biomass ratio (*1 + R*), conversion factor (*FC*).

Once the performance of the regression assumptions in the allometric equation has been inspected; the Shapiro-Wilk normality test showed a value of 0.96 (Table 2); the cumulative relative frequency percentages of the residuals are assimilated to a straight line, with respect to the probability of the normal distribution, their percentages tend to form a Gauss bell.

Table 2. Results of the Shapiro-Wilk, White and Durbin-Watson tests of the equation evaluated in the estimation of carbon stored in *Tectona grandis* L. f.

Model	***Shapiro-Wilk***	**Pr<W**	***White* test**	**Pr>ChiSq**	***Durbin-Watson* (DW)**
$C_{stored}\,(t) = ((\beta_0 + \beta_1.d + \beta_2.d^2 + \beta_3.d.h.D.FEB).((1+R).FC)$	0.96	0.0682	12.99	0.1121	2.01

The result of the Durbin-Watson statistic of independence of the frequency of the residues shows that there is no collinearity between variables (Table 2).

The dispersal of residues, in regard to the estimated values of stored carbon (Figure 2) in the allometric equation, does not express certainty of insufficiency. White's test value of 12.99 (Table 2) is not significant in the residuals (Pr> X^2-Sq = 0.1121), which means that there is no statistical evidence of heterocedasticity.

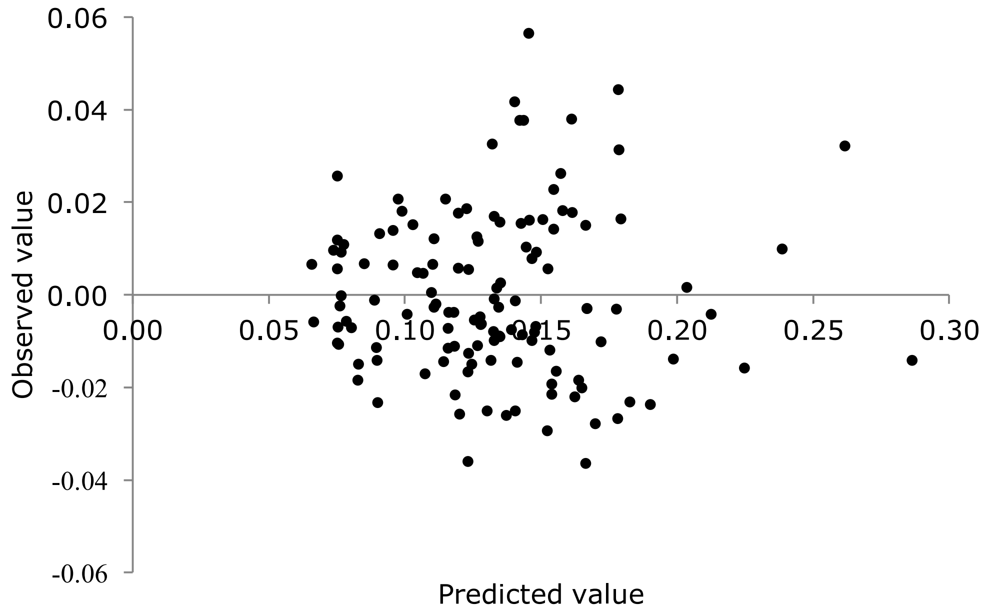


Figure 2. Residual distribution of the stored carbon equation for *Tectona grandis* L. f.

Based on the above, we proceeded to estimate the carbon stored in the trees of the commercial forest plantation of *T. grandis* under study. It was calculated that it has 140.37 ton ha^{-1} of biomass, the carbon stored per tree is 0.13 ton, the plantation stores 77.20 ton ha^{-1} of carbon in 6 ha.

The carbon estimation result is similar to that recorded by Novoa *et al*. (2006), who adjusted allometric equations and obtained an average of 72.65 t ha^{-1} of carbon stored in *T. grandis* plantations at 8 years of age established in *Nayarit*; differs from Jaramillo and Correa (2015) who determined that a 14-year plantation in the province of *El Oro, Ecuador*, stores 17.15 tons of carbon ha^{-1}; In *Costa Rica EcoBosques*® plantations, by adjusting mathematical equations, it was estimated for different ages (8, 12 and 16 years) that the carbon stored is 23.1 (ton ha^{-1}), 29.6 (ton ha^{-1}) and 44.5 (ton ha^{-1}) respectively; Jiménez and Landeta (2009) calculated values of 21.35, 25.56 and 11.42 ton ha^{-1} of accumulated carbon, in 8-year-old plantations of *T. grandis* from three sources (*Ecuador, Brazil* and *Costa Rica*) established in *Ecuador*; Patiño *et al.* (2018) made estimates of the carbon stored in plantations with the same five-year-old species established in *Tolima, Colombia*, determined that the plantation stores 27.20 ton ha^{-1} of carbon with the use of allometric equations.

The equation adjusted to estimate the carbon stored from the values of the parameters in Table 2, is defined as:

$$C_{stored}(t) = ((0.364129 \pm 0.05252.d + 0.002326.d^2 + 0.001067.d.h.D.FEB) .(1 + R).FC)$$

*Wh*ere:

C_{stored} = Stored carbon (ton ha^{-1}).

D = Normal diameter (cm).

h = Total height (m).

D= Basic density (g cm^3).

FEB = Biomass expansion factor

1 + R= Root/Total biomass ratio

FC = Conversion factor

Several studies have been carried out to determine the carbon stored through allometric equations for several species, among which the studies carried out by López-Reyes *et al.* (2016), who determined the carbon stored in the aerial biomass of plantations of *Hevea brasiliensis* (Willd. ex A. Juss) Müll. Arg. established in *Tabasco* of different ages, with the adjustment of allometric equations, determined that carbon varies for each age; in the 51-year-- plantation, the aerial stored carbon was 257.07 ton ha^{-1}, 32 year- plantation, 151.32 ton ha^{-1}, 25 year- plantation, 121.48 ton ha^{-1}, 15 years plantation, 108.57 ton ha^{-1}, 9 year- plantation, 35.79 ton ha^{-1} and 5 year- plantation, 26.28 ton ha^{-1}; these results are different from those obtained for the plantation of *T. grandis* established in *Michoacán* which stores 77.20 ton ha^{-1}, also differs with Cámara *et al.* (2013); these authors used equations to estimate the carbon stored in plantations established in *Tabasco*, from *Eucalyptus urophylla* S. T.

Blake, *Gmelina arborea* Roxb. and savannah of *Quercus oleoides* Schltdl. & Cham and determined that the carbon stored is 14.75 ton ha^{-1}, 15.54 ton ha^{-1} and 68.29 ton ha^{-1} respectively.

The models for estimating carbon stored in forest plantations are scarce in the literature, as well as research in which the biomass expansion factor in which the root biomass is contained is determined, due to the difficulty of sampling and to the high costs generated by this estimate (Schlegel, 2001; Sierra *et al*., 2001; Fonseca *et al*., 2009). Few studies have estimated the precise values of carbon content in the biomass of species of forest interest, which is why a biomass to carbon conversion factor of 0.5 is used (Husch, 2001).

Conclusions

The adjusted allometric equation, based on the goodness of fit indicators, the tests of normality of the residuals and the measures to estimate the predictive capacity of the model is considered appropriate to accurately estimate the carbon stored based on the normal diameter (*d*), total height (*h*), density (*D*), biomass expansion factor (*FEB*), radical biomass-total biomass ratio (*1* + *R*), conversion factor (*FC*).

T. grandis stores 77.20 ton ha^{-1} at 11 years established in *Michoacán* with a density of 1 666 ha^{-1} trees.

The adjusted allometric equation represents a significant tool, which is flexible because it allows indirect estimation of the carbon stored in trees (time and economic cost), can be adjusted to plantations with similar bioclimatic conditions.

It is feasible to incorporate the allometric equation into productivity systems to assess the potential of commercial forest plantations as environmental services in order to mitigate CO_2 emissions.

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Conflict of interests

The authors declare no conflict of interests.

Contribution by author

Javier Jiménez Pérez: research planning, development, analysis, information processing, structure and writing of the document; Ricardo Telles Antonio: planning, development, structure and document review; Eduardo Alanís Rodríguez: research planning and document review; José Israel Yerena Yamallel: research planning and document review; Dora Alicia García García: structure and document review; Martín Gómez Cárdenas: planning and development of field work, structure and document review.

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