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Article

Desarrollo de ecuaciones alométricas de biomasa para la regeneración de cuatro especies en Durango, México

Development of biomass allometric equations for the regeneration of four species in *Durango*, Mexico

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Resumen:

El objetivo del trabajo consistió en el desarrollo de ecuaciones alométricas para estimar la biomasa aérea por fracciones de grosor de la regeneración de *Arbutus arizonica, Juniperus deppeana, Quercus sideroxyla* y *Pinus cooperi* en la Unidad de Manejo Forestal (Umafor 1008) en el estado de Durango. Se utilizaron datos provenientes de 114 individuos (25, 29, 30 y 30, respectivamente), colectados mediante un muestreo destructivo para ajustar los modelos. La aditividad de las ecuaciones de estimación de biomasa se aseguró mediante el ajuste simultáneo de todas las ecuaciones, con el procedimiento estadístico denominado 3SLS (*Three-Stage Least Squares*). Los modelos desarrollados permiten estimar la biomasa en peso seco de los componentes, peso total, hojas, ramillas (< 0.5 cm), ramas finas (0.51 – 2.5 cm), ramas gruesas y tronco (> 2.51 cm). Las ecuaciones alométricas con mejor ajuste correspondieron al peso total, con valores de coeficiente de determinación ajustado de 0.97, 0.94, 0.95 y 0.97 para *Arbutus, Juniperus, Quercus* y *Pinus cooperi*, respectivamente. En general las ecuaciones mostraron un ajuste satisfactorio en cada una de las fracciones; con ellas se podrán hacer estimaciones no destructivas de la biomasa por categoría de grosor de la regeneración de las cuatro especies estudiadas, lo que mejorará las predicciones de biomasa y almacén de carbono por fracciones en los bosques con presencia de los cuatro taxa estudiados.

Palabras clave: Biomasa, carbono, modelos alométricos, fracción de grosor, regeneración.

Abstract:

The objective of this work was to develop allometric equations in order to estimate the biomass by thickness fractions of the regeneration of *Arbutus arizonica*, *Juniperus deppeana, Quercus sideroxyla* and *Pinus cooperi* trees of the Forest Management Unit (1008 Umafor) in the state of *Durango*. The data of 114 individuals (25, 29, 30 and 30, respectively) was used, collected through a destructive sampling, for adjusting the models. The additivity of the equations used to estimate the biomass is assured by the simultaneous adjustment of all equations, with the statistical procedure called 3SLS (Three-Stage Least Squares). The developed models make it possible to estimate the biomass in dry weight of the components, total weight, leaves, twigs (< 0.5 cm), thin branches (0.51 - 2.5 cm), thick branches and trunk (> 2.51 cm). The allometric equations with the best fit corresponded to the total weight, with adjusted coefficient of determination values of 0.97, 0.94, 0.95 and 0.97 for *Arbutus*, *Juniperus*, *Quercus* and *Pinus cooperi*, respectively. In general, the equations showed a satisfactory adjustment in each of the fractions; they allow non-destructive estimates of biomass by category of thickness of the regeneration of the four studied species, which will improve the predictions of biomass and carbon storehouse by fractions in the forests with the presence of the four studied taxa.

Key words: Biomass, carbon, allometric models, thickness fraction, regeneration.

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Introduction

The allometric models constitute important tools for an appropriate estimation of the biomass and carbon in forests and are employed in the inventories of fuels for the estimation of loads of different fractions of both adult and regenerated trees.

The work of allometries generally considered the fractions of biomass of leaves, trunk, and branches according to their thickness; the categories of twigs (<0.5 cm), thin branches (usually 0. 5 to 2.5 cm) and medium and thick branches (usually >2.5 and 7.5 cm, respectively) are the most common (Reed and Toméb, 1998; Álvarez *et al.,* 2005; Antonio *et al.,* 2007; Muñoz *et al.,* 2008; Pérez-Cruzado *et al.,* 2011a, 2011b; González-García *et al.,* 2013; Jiménez *et al.,* 2013; Vega-Nieva *et al.,* 2015).

The allocation of biomass in fractions changes in relation to the normal diameter (Fontes *et al.,* 2006; Antonio *et al.,* 2007; Vega-Nieva *et al*., 2015); this makes it necessary to evaluate the allocation at different stages of development of the masses. For example, in the work of Antonio *et al.* (2007), there were differences in the allometries developed for *Eucalyptus globulus* Labill., according to the status of development of the mass, and the development of the specific models in young trees with small dimensions. In Mexico, the biomass of the fractions of leaves, twigs, and branches has been observed to represent up to 55 % that in young trees with diameters of less than 15 cm; in contrast, in trees with diameters above 20 cm, there is a higher concentration of biomass in the main stem (Soriano-Luna *et al.,* 2015; Vargas-Larreta *et al*., 2017).

The modeling of the amount of biomass in each of these fractions over different ages is important for carbon accounting systems (Pérez-Cruzado *et al.*, 2011b; González-García *et al*., 2013). Also, it is important to know the biomass present in different fractions resulting from the differences in patterns of accumulation of nutrients between fractions and ages, which is relevant for assessing the nutritional sustainability of the management of the forest masses, based on such management practices as the removal of finer fractions, or the ages of rotation in the balance of nutrients of the arboreal masses (Brañas *et al.*, 2000; Dambrine *et al.*, 2000; Laclau *et al.*, 2000; Merino *et al.*, 2003, 2005).

In Mexico, allometric models have been developed for different needs (Morfín-Ríos *et al.* 2012; Ruiz-Díaz *et al.* 2014), and most of the available studies on biomass allometries focus on adult trees (Acosta-Mireles *et al.,* 2002; Díaz-Franco *et al*., 2007; Návar-Cháidez, 2009; Aguirre-Calderón and Jiménez-Pérez, 2011), while there is relatively little research on the estimation of biomass during the regeneration stage (Vargas-Larreta *et al.* 2017; Montes de Oca-Cano *et al*. 2009; Montes de Oca-Cano *et al*., 2012). This information is of special interest, due to the need to know the amounts of carbon captured in the forests during all stages of growth and fractions of the trees (Vargas-Larreta *et al.* 2017).

The objective of this study was to develop allometric equations for estimating the biomass by thickness fractions of four species at the regenerationn stage in mixed and irregular ecosystems of *Durango*.

Materials and Methods

The study was carried out at the Regional Forest Management Unit (Umafor) No. 1008, located to the southwest of the state of *Durango*, at the coordinates 23°06'59'' and 24°11'38'' N, and 105°55'56'' and 105°10'31'' W. The study area includes parts of the municipalities of *Durango*, *San Dimas* and *Pueblo Nuevo*, and covers a surface of approximately 558 thousand hectares. It comprises seven different types of climate according to Köppen's classification modified by García (1988), the most predominant of which are warm-humid $C(w_2)$, semi-warm sub-humid (A) $C(w_2)$ and semi-cold sub-humid $Cb'(w_2)$; with annual precipitations of 800 to 1 200 mm (SRNyMA-Conafor, 2007). The most important plant communities of the region consist of pine forest, followed by pine-oak forest associations and, in a lower proportion, low deciduous forests, grasslands, and the area of rain-fed agriculture (Inegi, 2012).

Sampling for the destructive analysis

114 regenerated individuals were selected: 30 specimens of *Pinus cooperi* C.E. Blanco, 30 of *Quercus sideroxyla* Humb. & Bonpl., 29 of *Juniperus deppeana* Steud. and 25 of *Arbutus arizonica* Sarg. All specimens were free of pests, diseases, and physical and mechanical defects; they were randomly selected to represent the category of the regeneration and thicket stages, with a base diameter of 10 cm or less. The dendrometric variables measured in the field for each tree were: base diameter (*bd*), diameter at breast height (*dbh*) and crown diameter (*cd*), with two crosswise measurements. Once the trees were felled, the total height (*h*), the height of the dry crown (*hdc*), the height of the living crown (*hlc*), the length of the dry crown (*ldc*) and the length of the living crown (*llc*) were measured, as recommended by Gómez-García *et al.* (2013). All measures were expressed in centimeters.

Each individual was felled and stored in plastic bags in order to prevent loss of moisture. Each was labeled with an identification key composed of the number of the specimen and the date of collection.

Laboratory analysis

Each tree was divided into the following thickness fractions: leaves, twigs (<0.5 cm), thin branches (>0.51 - 2.5 cm), trunk and thick branches of > 2.51 cm. The total living weight per fraction was estimated, with a (Ohaus explorer EX4202) precision scale, in 0.001 g for the biomass of the leaves and smaller branches; for the thin and thick branches and the stem, the estimated weight was 0.01 g. The individual fractions were bagged and labeled, and then placed in a (Felisa FE-294A) drying oven, for 8 to 10 days, at 75 °C, until a constant dry weight was attained.

Adjustment of biomass equations

A non-linear regression analysis between the variables measured in the field (*bd*, *h*, *hdc*, *hlc*, *cd*, *dbh*, *ldc* and *llc*) and the measurements of load per fraction (twigs, thin branches, thick branches and trunk, leaves, and total) was carried out in the laboratory. For the estimation of the dry weight different non-linear equations were tested, with different combinations of predictive variables; the best results were adjusted by least-squares, using the model of the SAS/ETS^{TM} software (SAS, 2009).

The equations were adjusted simultaneously for thickness fraction and for total thickness in order to ensure the additivity (Álvarez-González *et al.*, 2007). This is one of the most important properties with which the equations of biomass of the various components must comply (Cunia, 1986; Parresol, 1999; Antonio *et al.,* 2007), namely, that the sum of the estimates of the weights of all components or fractions must be equal to the estimated total weight of the tree. This is achieved through the simultaneous adjustment of the different mathematical models proposed for each fraction. The technique is based on the adjustment of a system of seemingly unrelated equations formed by the regression functions of the *k* tree components along with the total biomass (Álvarez-González *et al.,* 2007).

$$
\begin{gathered}
\widehat{w}_1 = f_1\,(x_1) \\
\widehat{w}_2 = f_2\,(x_2) \\
. \\
. \\
. \\
. \\
\widehat{w}_k = f_k\,(x_k) \\
\widehat{w}_{total} = f_{total}\,(x_1, x_2, \dots, x_k)
\end{gathered}
$$

Where:

$\widehat{w}_k$ = Estimated biomass

x_k = Set of explanatory variables

In this system, the equations of the tree fractions need not all have the same mathematical expression or the same predictive variables. The independent variables in the total biomass model are all regressor variables that appear in the mathematical expressions of each component. The parameters of the equations were obtained simultaneously with the Three-Stage Least Squares methodology (3SLS); the *MODEL* procedure model of the SAS/ETS™ was utilized for this purpose (SAS, 2009). In the adjustment of biomass models it is important to check the constancy of the variance of the residuals (Picard *et al.*, 2012) in order to rule out problems of heteroskedasticity; that is to say, that the variance of the errors will not be constant (Parresol, 2001). White (1980) contrast was applied in order to analyze the presence of heteroskedasticity. The heteroskedasticity is corrected during adjustment of the equations, through the weighing of each observation by the inverse of its variance (σ_i^2). Because this variance is unknown, it is assumed that it can be modeled with a potential function $\sigma_i^2 = x_i^k$, where x_i is a function of one or more of the independent variables of the model. The *k*-value of the exponent and the variables to be included (x_i) are determined by the errors of the adjusted model without weights ($\hat{e}_i$), as the dependent variable in the potential model of variance of the error (Park, 1966; Harvey, 1976), and by testing different combinations of variables and exponents, in order to optimize the result of the linear adjustment derived from taking logarithms in the following expression:

$$\hat{e}_i^2 = x_i^k \rightarrow log\hat{e}_i^2 = \gamma + k \cdot logx_i$$

Criteria for the selection of models

The criteria for determining the best model were the graphic analysis of the residuals; the coefficient of determination (R^2), which reflects the total explained variability, and the square root of the mean square error (RMSE), which analyzes the accuracy of the estimates, according to the following equations:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2}$$

$$REMC = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n - p}}$$

Where:

y_i, $\hat{y}_i$, and $\bar{y}_i$ = Observed value, estimated value and average of the dependent value

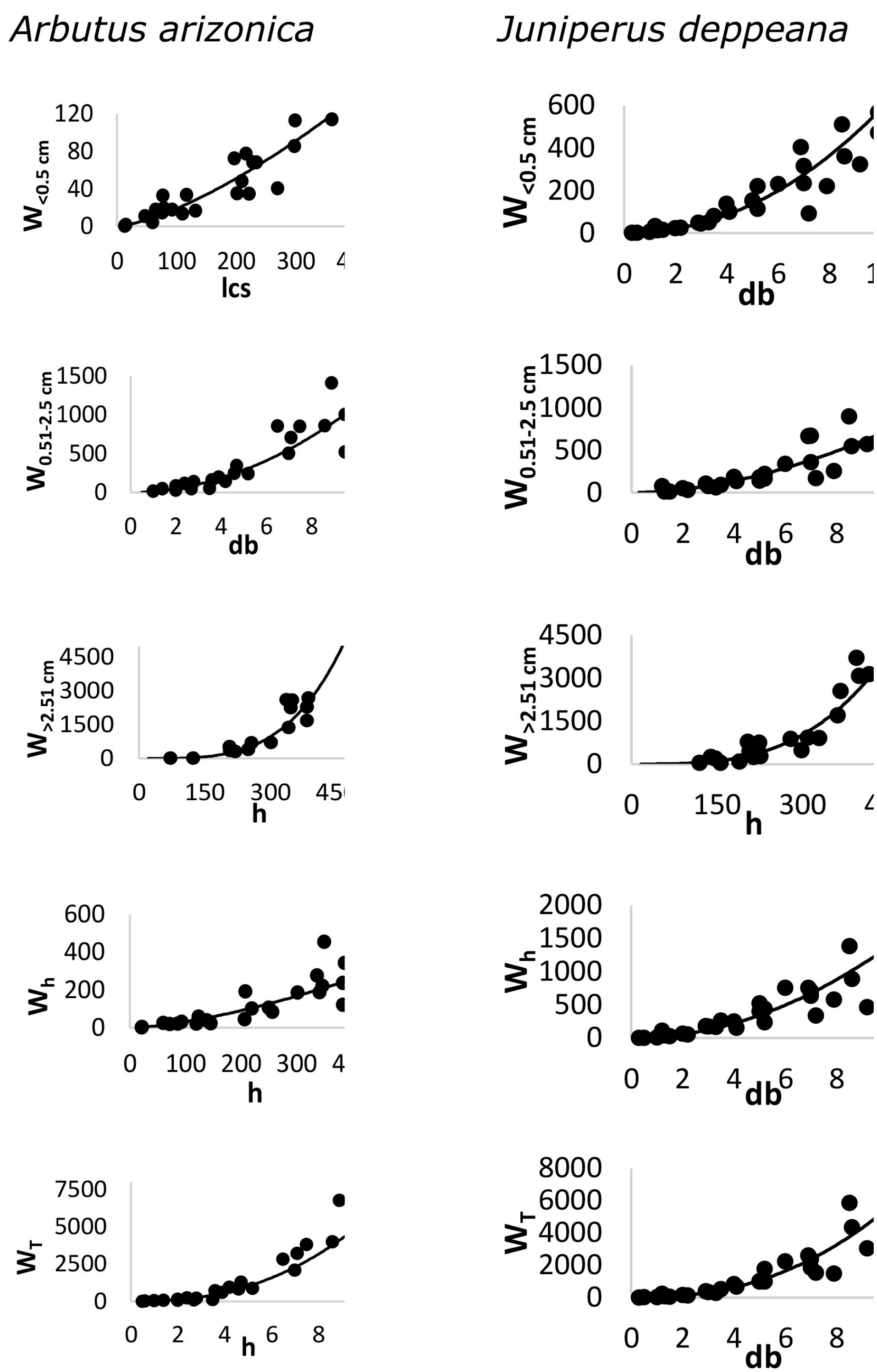
n = the total number of observations used to adjust the model

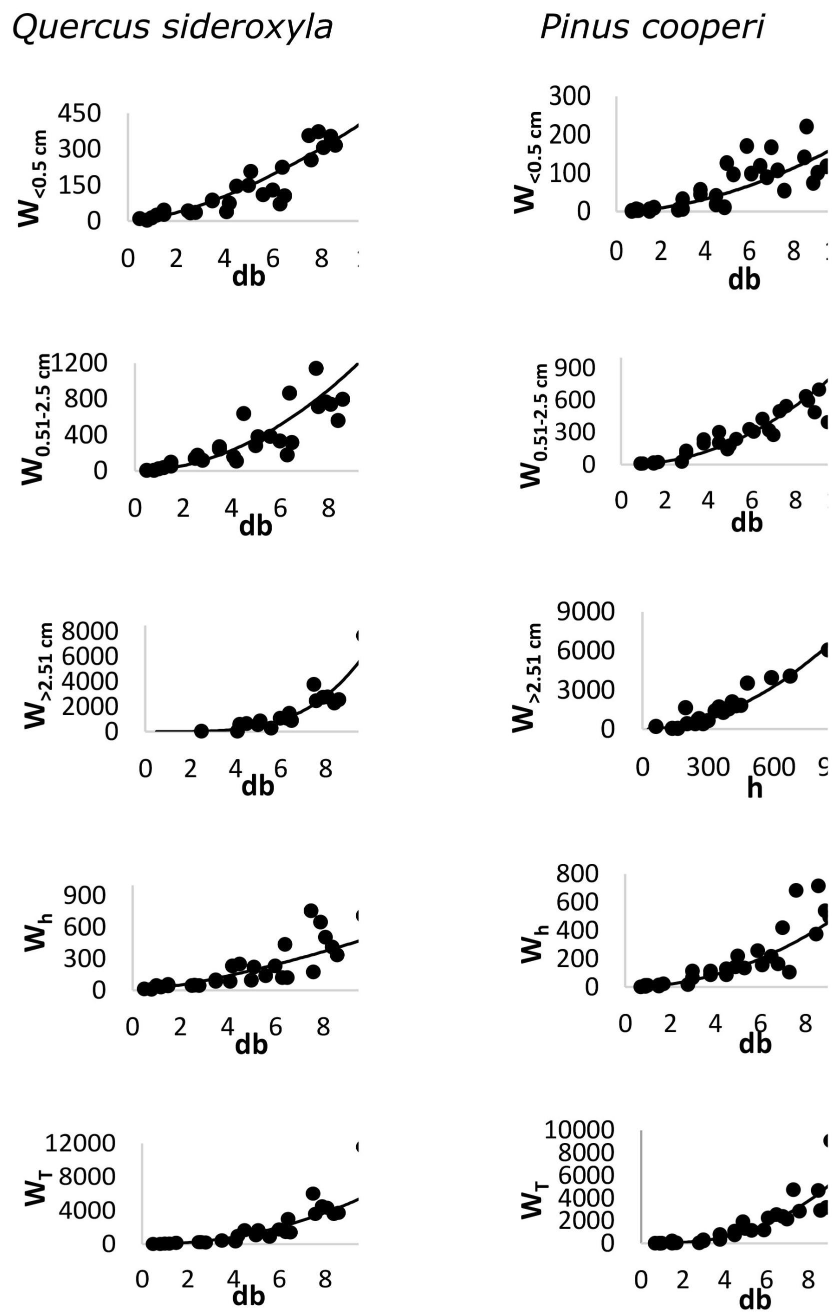
p = Number of parameters of the model

In addition to the statistics described above, one of the most efficient ways to assess the capacity of adjustment of a model is visual inspection; for this reason the residual plots were analyzed against predicted values of the dependent variable.

Results and Discussion

Figure 1 shows the graphic representation of the values of the biomass of fractions by component against the independent variable that had the greatest influence on the allometric equations for *Arbutus arizonica*, *Juniperus deppeana sideroxyla*, *Quercus* and *Pinus cooperi*.


Arbutus arizonica
Juniperus deppeana
W<0.5 cm
lcs
db
W0.51-2.5 cm
W>2.51 cm
h
Wh
WT



db = Base diameter (*bd)*; *h* = Total height; *lcs* = Length of the dry crown (*ldc)*;*lcv* = Length of the living crown (*llv)*; $W_{<0.5\ cm}$ = Weight of the thin branches; $W_{0.51\text{-}2.5\ cm}$ = Weight of the thick branches; $W_{>2.51\ cm}$ = Weight of the main stem; W_h = Weight of the leaves (W_l); W_T = Total weight.

Figure. 1. Relationship between the biomass in grams of the different components and the most influential explanatory variables of the model by species.

Table 1 shows the expression of the models that exhibited the best results in the individual adjustment per component for the estimation of the biomass by thickness fraction and total thickness of the studied species.

Table 1. Selected models for the estimation of the biomass by thickness fraction and total thickness of *Juniperus deppeana* Steud., *Arbutus arizonica* Sarg., *Quercus sideroxyla* Humb. & Bonpl. *and Pinus cooperi* C.E. Blanco at the regeneration stage.

Species	Component	Model
J. deppeana	$W_{<0.5\ \mathrm{cm}}$	$W_{<0.5} = a_1 * bd^{a_2} * cd$
	$W_{0.51-2.5\ \mathrm{cm}}$	$W_{0.51-2.5} = a_3 * bd^{a_4} * llc$
	$W_{>2.5\ \mathrm{cm}}$	$W_{>2.51} = a_5 * h^{a_6} * cd$
	W_l	$W_l = a_7 * bd^{a_8} * llc$
	W_T	$W_T = a_1 * bd^{a_2} * cd + a_3 * bd^{a_4} * llc + a_5 * h^{a_6} * cd + a_7 * bd^{a_8} * llc$
A. arizonica	$W_{<0.5\ \mathrm{cm}}$	$W_{<0.5} = a_1 * ldc^{a_2}$
	$W_{0.51-2.5\ \mathrm{cm}}$	$W_{0.51-2.5} = a_3 * bd^{a_4} * h$
	$W_{>2.5\ \mathrm{cm}}$	$W_{>2.51} = a_5 * h^{a_6} * bd$
	W_l	$W_l = a_7 * h^{a_8} * bd$
	W_T	$W_T = a_1 * bd^{a_2} * ldc + a_3 * bd^{a_4} * h + a_5 * h^{a_6} * bd + a_7 * h^{a_8} * bd$
Q. sideroxyla	$W_{<0.5\ \mathrm{cm}}$	$W_{<0.5} = a_1 * bd^{a_2} * cd$
	$W_{0.51-2.5\ \mathrm{cm}}$	$W_{0.51-2.5} = a_3 * bd^{a_4} * cd$
	$W_{>2.5\ \mathrm{cm}}$	$W_{>2.51} = a_5 * bd^{a_6} * cd$
	W_l	$W_l = a_7 * bd^{a_8} * cd$
	W_T	$W_l = a_1 * bd^{a_2} * cd + a_3 * bd^{a_4} * cd + a_5 * bd^{a_6} * cd + a_7 * bd^{a_8} * cd$
P. cooperi	$W_{<0.5\ \mathrm{cm}}$	$W_{<0.5} = a_1 * bd^{a_2} * cd$
	$W_{0.51-2.5\ \mathrm{cm}}$	$W_{0.51-2.5} = a_3 * bd^{a_4}$
	$W_{>2.5\ \mathrm{cm}}$	$W_{>2.51} = a_5 * h^{a_6} * bd$
	W_l	$W_l = a_7 * bd^{a_8} * cd^{a_9}$
	W_T	$W_T = a_1 * bd^{a_2} * cd + a_3 * bd^{a_4} + a_5 * h^{a_6} * bd + a_7 * bd^{a_8} * cd^{a_9}$

$W_{<0.5\ \mathrm{cm}}$ = Dry weight of the twigs (g); $W_{0.51-2.5\ \mathrm{cm}}$ = Dry weight of the thin branches (g); $W_{>2.51\ \mathrm{cm}}$ = Dry weight of thick branches and main stem (g); W_l = dry weight of leaves (g); W_T =Total Weight (g); *bd* = Base diameter of each plant (cm); *h* = total height of each plant (cm); *cd* = Crown diameter of each plant (cm); *llc* = Length of the living crown of each plant (cm); *ldc* = Length of the dry crown of each plant (cm).

Table 2 shows the estimates of the parameters obtained by means of simultaneous adjustment, the approximate standard errors and the statistical goodness of fit, as well as the weights used in the weighting to correct the heterosckedasticity in the fractions that exhibited this problem.

Table 2. Estimation of the parameters, and statistical goodness-of-fit obtained for the equations of the biomass per thickness fraction through simultaneous adjustment by 3SLS.

Species	Component	Param	Estimate	S.E	RMSE (g)	Weights	R^2
J. deppeana	Twigs	a1	0.1957	0.0863	55.64		0.88
		a2	1.0708	0.2112			
	Thin branches	a3	0.1441	0.0778	123.27		0.86
		a4	1.1372	0.2534			
	Thick branches	a5	3.7E-6	4.8E-6	305.20	$1/\sqrt{(h)}^{2.9}$	0.92
		a6	2.5272	0.2181			
	Leaves	a7	0.2847	0.1387	162.94	$1/\sqrt{(db)}^{2.1}$	0.88
			1.2422	0.2522			
	Total weight				507.94		0.94
A. arizonica	Twigs	a1	0.0073	0.0158	15.19		0.87
		a2	1.6580	0.3734			
	Thin branches	a3	0.2060	0.0556	120.63	$1/\sqrt{(db)}^{3.21}$	0.90
		a4	1.1329	0.1420			
	Thick branches	a5	0.0032	0.0040	268.43		0.95
		a6	1.9222	0.2058			

	Leaves	a7	0.3732	0.4947	69.95	$1/\sqrt{(h)}^{2.4}$	0.78
		a8	0.7810	0.2361			
	Total weight				322.40		0.97
Q. sideroxyla	Twigs	a1	0.0396	0.0174	80.93	$1/\sqrt{(db)}^{1.9}$	0.93
		a2	1.9577	0.2044			
	Thin branches	a3	0.3768	0.0827	237.06	$1/\sqrt{(db)}^{3.6}$	0.88
		a4	1.2930	0.1181			
	Thick branches	a5	0.0683	0.0291	598.09	$1/\sqrt{(db)}^{3.7}$	0.94
			2.6210	0.2022			
	Leaves	a7	0.1640	0.0901	132.58		0.79
		a8	1.3279	0.2562			
	Total weight				905.08	$1/\sqrt{(db)}^{2.5}$	0.95
P. cooperi	Twigs	a1	0.1024	0.0652	35.75	$1/\sqrt{(db)}^{1.12}$	0.69
		a2	0.8569	0.2690			
	Thin branches	a3	8.2417	1.6303	129.95	$1/\sqrt{(db)}^{3.7}$	0.79
		a4	2.0242	0.1038			
	Thick branches	a5	0.0817	0.0394	397.83		0.96
		a6	1.3391	0.0731			
	Leaves	a7	0.0255	0.0439	82.21	$1/\sqrt{(db)}^{1.7}$	0.84
		a8	1.1890	0.3194			
		a9	1.3917	0.3716			
	Total weight				354.47		0.97

Param = Model parameters by component; S.E = Approximate Standard Error; RMSE = Root of the mean square error; R^2 = Coefficient of determination.

Simultaneous adjustment with the 3SLS technique provided an estimate of the statistical goodness-of-fit that is very similar to that of the individual adjustment. The majority of the species exhibited heteroskedasticity in most of their biomass fractions. This problem was corrected by weighted regression as in other tree biomass estimations (Parresol, 2001; Álvarez-González *et al.,* 2007). Some fractions exhibited no heteroskedasticity according to White's test, possibly because of the relatively small range of diameters and weights sampled, as the trees were young.

Figure 2 shows the observed values compared to those predicted for the different thickness fractions, for the leaves and for the total weight. The distribution of the cloud of dots on the diagonal line indicates that the models provide estimates with a low bias.

In general, the equations had a satisfactory adjustment and account at least for 69 % of the variability observed. The biomass of the fractions of the leaves and twigs exhibited fair to good adjustments, possibly due to the variability of the structures of the crown and the number of branches (Pardé, 1980). For the fractions of the leaves and twigs, the coefficients of determination were 0.84-0.69, 0.78-0.87, 0.88-0.88 and 0.79-0.93 for *P. cooperi*, *A. arizonica*, *J. deppeana* and *Q. sideroxyla*, respectively. The fractions of the crown were generally considered as the most difficult to model (Muñoz *et al.*, 2008).

The goodness-of-fits for *Pinus* are similar to those reported by previous nationwide studies for biomass allometries for this genus (Montes de Oca-Cano *et al*. 2009; Montes de Oca-Cano *et al*., 2012; Vargas-Larreta *et al*., 2017). Montes de Oca-Cano *et al*. (2009) adjusted the equations of biomass per component for *Pinus durangensis* trees aged 3 to 10 years; according to their results, the stem had the best statistical adjustment, with an R^2 = 0.86, while the coefficients of determination of the branches and leaves were 0.74 and 0.74, respectively; Montes de Oca-Cano *et al.* (2012) documented similar values, with a R^2 of 0.73 for the leaves. Vargas-Larreta *et al*. (2017) reported values of R^2 = 0.74 for the fraction of the leaves of *Pinus cooperi*, with the variables diameter and height. In the present study, the value of R^2 was 0.84 for the leaves of *Pinus cooperi*, which improved the adjustment by adding the diameter of the crown to the utilized model.

Geudens *et al.* (2004) obtained the best fit for the aerial biomass in *Pinus sylvestris* trees aged 1 to 4 years, for the variables diameter and height (dbh^2h), with a R^2 of 0.95; these results are similar to those reported in the present document, with a coefficient of determination R^2 of 0.97. Vargas-

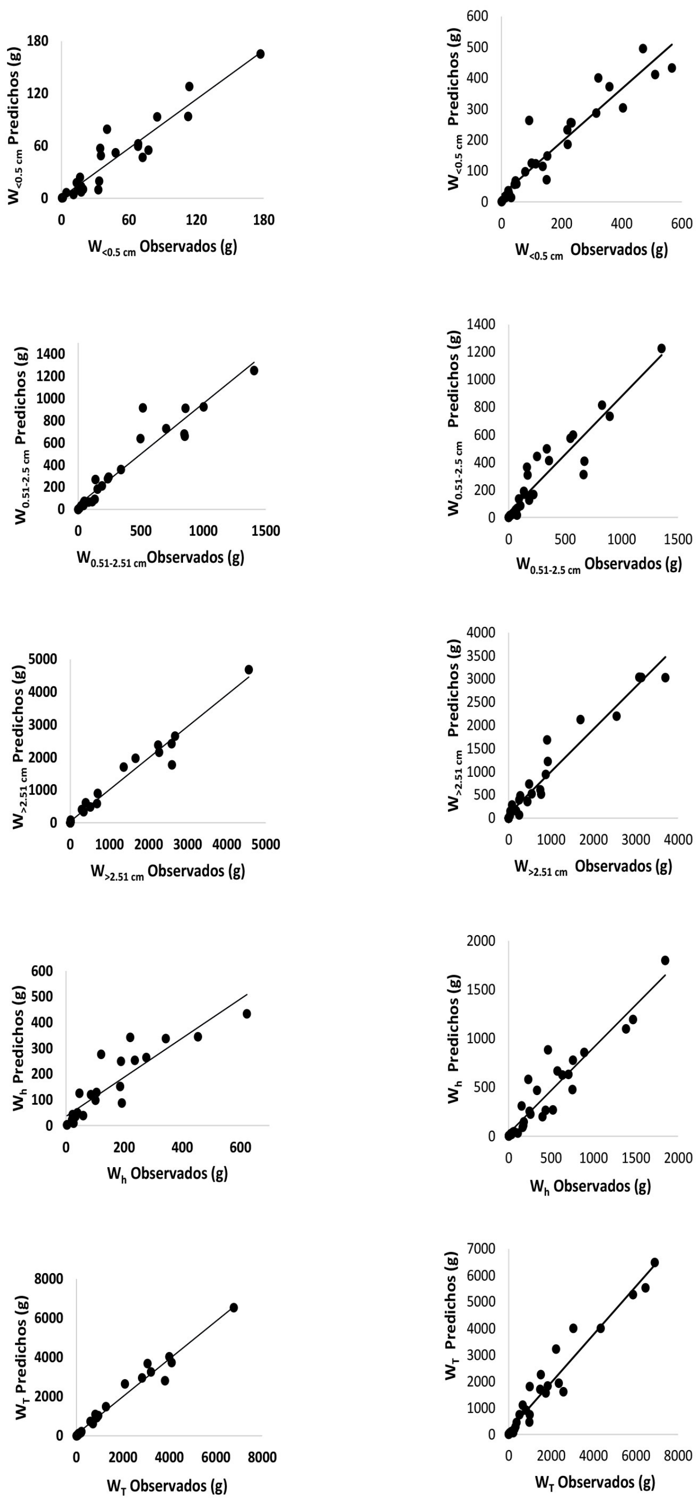
Larreta *et al.* (2017) cite values of R^2 of 0.94 and 0.90, respectively, for the best model of total biomass of the regeneration of *Pinus cooperi* and *P. leiophylla*; these values are very similar to those estimated in this study for *P. cooperi*.

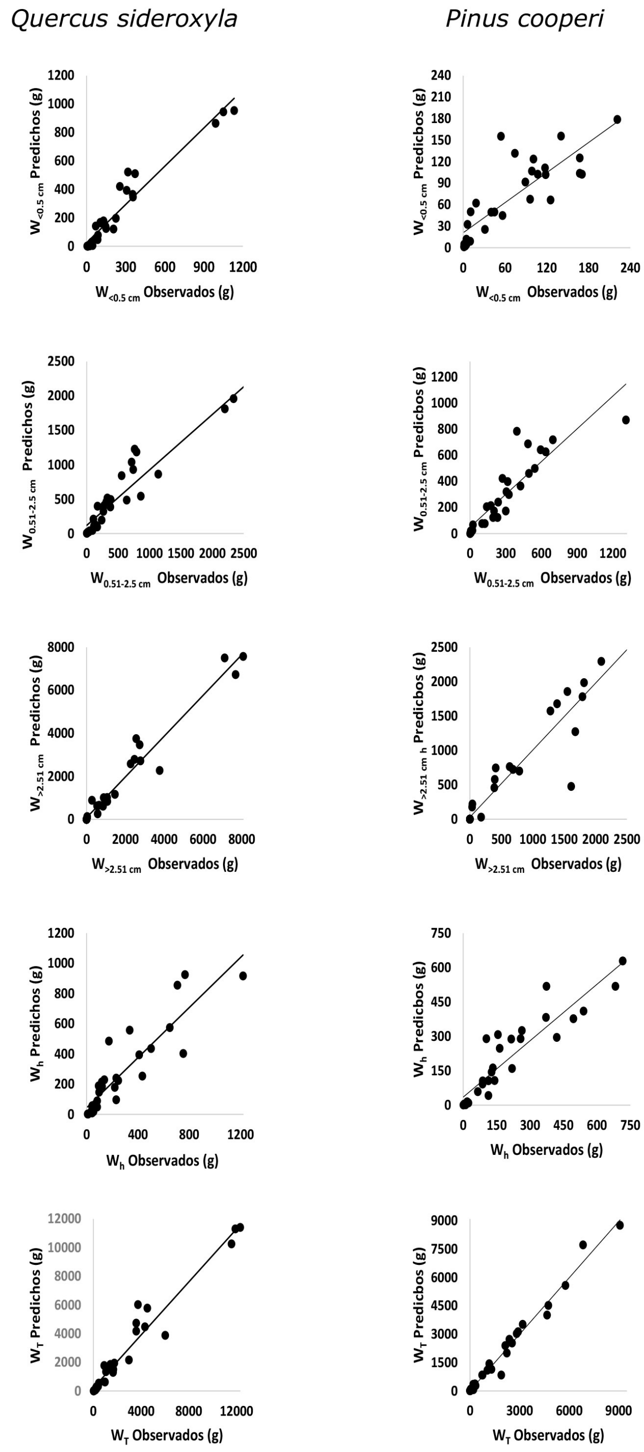
The goodness of fits of the adjustments for *Quercus* are also similar to those cited in the literature. González (2008) estimated the biomass for *Quercus* spp. in selected trees within the categories of natural regeneration of seedlings with heights of 2 m and trees at pole stage with heights of up to 21 m. The best model for estimating the total biomass included the normal diameter as an independent variable, with a coefficient of determination of 0.96. In the present work, in which simultaneous adjustments were utilized, a similar R^2 of 0.96 was obtained. In northwestern Spain, Gómez-García *et al.* (2013) estimated the biomass of *Quercus robur* L. by fractions and by total weight; the best fit for the fraction of the leaves, R^2 = 0.78, was obtained by using the *dbh* as the explanatory variable. This is consistent with the coefficient of determination estimated for the leaves of *Quercus* (0.79) in *Durango*, through the use of the predictive variables *bd* and *cd*.

For the genus *Juniperus*, the use of the base diameter generated good results in previous works. Thus, in Texas, Reemts (2013) points out that, in small *Juniperus ashei* J.Buchholz trees (with a basal diameter of < 15 cm), the allometric equations based on the *bd* and dbh^2h had a better adjustment for the total biomass than the equations based only on the height of the tree and the volume of the canopy (R^2= 0.95-0.97 *versus* R^2=0.71-0.77). Rodríguez-Laguna *et al.* (2009) calculated coefficients of determination of 0.97 for *Juniperus flaccida* Schltdl. using a potential model whose predictive variable was the normal diameter.

In general, the coefficients of determination for *Arbutus arizonica* were good, and the best was for the total weight, with a R^2 value of 0.97. This result is similar to that obtained by Harrington *et al.* (1984), who estimated the total biomass for *Arbutus menziesii* Pursh using the normal diameter as the explanatory variable, with a coefficient of determination of 0.97. Another study, conducted by Vargas-Larreta *et al*. (2017), obtained coefficients of determination of 0.74 and 0.92 for the leaves and for the total weight of *Arbutus bicolor* S. González,M. González & P.D. Sørensen, respectively, using as predictive variables diameter and height. Ter-Mikaelian and Korzukhin (1997) obtained coefficients of determination of 0.83 for the biomass of the leaves of *Arbutus menziesii* by using the diameter at breast height as a predictive variable. In the study documented herein, the adjustment for the leaves accounted for 78 % of the variability observed.

Arbutus arizonica *Juniperus deppeana*





Observados = Observed; *Predichos* = Predicted

Figure 2. Graphics of observed values compared to predicted values of biomass per thickness fraction, for the leaves and for the total biomass of the four studied species.

Although the base diameter was the best explanatory variable for all components of the biomass, the height and length of the living and dry crown improved the allometric models for the fractions of the branches and leaves —similarly to what has been observed in other studies (Williams *et al.,* 2005; Antonio *et al*., 2007; Paul *et al.,* 2008; Vega-Nieva *et al*., 2015) —, but at the expense of a greater sampling effort in order to apply the models (Gómez-García *et al.,* 2013).

Conclusions

Systems of equations were developed for estimating the biomass per thickness fraction and for the total thickness of individuals of the species *Arbutus arizonica*, *Juniperus*, *Quercus sideroxyla* and *Pinus cooperi* at the regeneration stage. These equations allow performing non-destructive estimations of the biomass of the four studied species and improve the estimates of the allocation of biomass, carbon and nutrients by fractions at the different stages of the forest masses. It is important to continue to work with and improve this type of models and to study the biomass of the regenerations of other relevant species.

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Conflict of interest

The authors declare no conflict of interest.

Contribution by author

Favián Flores Medina: Field work and drafting of the manuscript; Daniel José Vega-Nieva: experimental design, review of the manuscript and coordination of the revisions; Juan Gabriel Álvarez-González, Ana Daria Ruiz-González, Carlos Antonio López-Sánchez, José Javier Corral-Rivas and Artemio Carillo Parra: review of the manuscript and statistical analysis.

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