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Article

Estimation of the above-ground biomass of *Pinus cembroides* Zucc. and *Pinus halepensis* Mill. in *Saltillo, Coahuila*

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Abstract:

The Allometric models to estimate biomass, carbon and carbon dioxide, are of great importance in forest modeling, for these it is possible to quantify the mitigation of greenhouse gas emissions. The objective of present study was to adjust an allometric models for biomass aboveground estimation in a plantation of *Pinus cembroides* and *P. halepensis*. The aboveground was estimated with the indirect method (Adelaide Method) with a sample of 50 trees by species. The study was made in two areas: *Cuauhtémoc* and *El Recreo*, of *Saltillo*, *Coahuila*. For each biomass component of leaves-branches, stem and total six models were adjusted, using independent variables of diameter and height, selecting the best model according to the adjusted determination coefficient ($_{adj}R^2$), standard error (Syx) and the significance of the regression parameters. The results indicated that the diameter adequately estimates the biomass by component of *P. cembroides* ($_{adj}R^2$ average of 0.86), for *P. halepensis* the biomass is estimated with diameter and height ($_{adj}R^2$ of 0.79 on average). The indirect method is a good estimator of aboveground biomass in both species, the best adjustments of models can be used to quantify carbon storage and carbon dioxide in the region.

Key words: Adjustment, aboveground biomass, components, Adelaide method, allometric models, regression parameters.

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Introduction

Today, there is recognition of the importance of forests as a means to mitigate greenhouse gas (GHG) emissions, particularly those of carbon dioxide (CO_2), which are the cause of the climate change. For this purpose, natural areas are preserved and forest plantations that favor carbon storage for long periods are established (Návar *et al.*, 2001; Aguirre-Calderón and Jiménez-Pérez, 2011).

The biomass of a forest is of great importance, because it makes it possible to determine the amount of carbon (C) that exists in a conservation area, or the potential amount that is likely to be released into the atmosphere by the combustion process (Brown *et al.*, 1996). The forest biomass is defined as the weight of the organic matter that exists in a particular forest ecosystem above and below the ground, and it is normally is measured in tons per hectare of dry weight (Schlegel *et al.*, 2000).

The estimation of the above-ground biomass of any component of a tree requires a direct or indirect analysis. The direct method consists in cutting down the tree and weighing the samples of each component and subsequently determining the dry weight (Díaz *et al.*, 2007). The indirect method can be based on the stem volume and uses the basic density to estimate the dry weight and a factor of expansion to calculate the total dry weight (Schlegel, 2001; Segura and Andrade, 2008). Adelaide is an indirect method that involves taking a branch which is called hand unit or reference unit; this has to be representative as to the shape and leaf density of the species of interest and is used to calculate the number of branches present in each sampled tree (Foroughbakhch *et al.*, 1996).

If the biomass and the carbon (C) concentration per compartment are known, the total carbon content of a taxon can be estimated with greater precision; although the carbon dioxide concentration in the plants is approximately 50 % of the dry biomass, this value varies depending on the form of growth (Becerril *et al.*, 2014; Pompa and Yerena, 2014).

The biomass of a forest is determined by allometric models for each particular species (Brown, 1997), since the use of the equations developed in different regions has limitations due to the conditions that govern the growth of the trees, as well as their genetics, climate and soil (Álvarez, 2008). Some studies have shown that the normal diameter is the independent variable that efficiently predicts the total biomass in *Pinus halepensis* Mill., *P. pseudostrobus* Lindl., and *P. devoniana* Lindl., with a coefficient of determination of 0.73 (Mendez-González *et al.*, 2011; López, 2012; Domingo *et al*., 2016). Xiao and Ceulemans (2004) obtained the total biomass of *P. sylvestris* L. using the variables normal diameter, height and crown diameter, with an $_{adj}R^2$ of 0.98. Because each species and region should have a model for estimating its biomass, the present study was carried out with the purpose of adjusting allometric models for calculating the above-ground biomass of *P. cembroides* and *P. halepensis*.

Materials and Methods

Study Area

The research was carried out in plantations aged 22 years, located in two *ejidos* of *Saltillo*, *Coahuila*. The first one, called *Cuauhtémoc*, is located at the coordinates 25°16'45.60" N and 100°59'20.49" W and an altitude of 2 162 m; and the second, named *El Recreo*, located at the coordinates of 25°14'43.94" N and 101°04'26.47" W and an altitude of 1 982 m. In the area there are pine forests, microphyllous and rosetophyllous desert shrubs; the climate is arid semi-warm (BS_ohw) and semi-arid temperate (BS_1kw), with summer rains, a mean annual precipitation of 125 to 400 mm, a mean annual temperature of 14 to 18 °C, and Lithosol and Calcic Xerosol soils (García, 1998).

Indirect method for estimating the biomass

The Adelaide method (Foroughbakhch *et al*., 1996) was utilized. An average tree in terms of diameter and height was selected from the plantation and divided into three sections, and the (Adelaide) method was applied to each section. A representative branch was cut only once. Later, the number of times that the representative branch of each section could be contained in its respective section of the tree was calculated. 50 healthy trees that were considered representative of the categories of normal diameter and height were sampled for each species. In each individual, the normal diameter (cm) and the smallest and largest diameter of each section (cm) were measured with a Forestry Suppliers Metric Fabric Diameter Tape Model 283D/5M, and the heights of each section (m) were measured with a *Truper* FH-5ME measuring tape.

The representative branch was carried to the laboratory and placed in a *Blue M.* drying oven at a temperature of 105 °C until it reached its constant weight (Schlegel *et al.*, 2000); after drying, the dry weight was obtained with a Torrey Pizza Controller PZC-5 scale, with a capacity for 5 kg and a 1 g accuracy. Once the value of the dry weight of each representative branch had been calculated, it was multiplied by the estimated number of branches of the corresponding section; the three sections were added to obtain the dry weight of the leaves-branches of each tree. The dry weight of the stem was obtained by multiplying the volume by the basic density. The stem volume was determined using the Smalian formula (1), and the basal area (g), using the second formula (2).

$$V = \left(\frac{g_1 + g_2}{2} \right) * L \quad (1)$$

$$g = \frac{\pi}{4} * D^2 \quad (2)$$

Where:

g = Basal area (m^2)

g_1 = Smallest basal area of the section (m^2)

g_2 = Largest basal area of the section (m^2)

L = Log length of the section (m)

D = Diameter (m)

The basic density in *P. cembroides* is 450 kg m^{-3} (Ordoñez *et al.,* 2015) and 494 kg m^{-3} in *P. halepensis* (Ruano *et al.*, 2012). The total dry weight of the tree was calculated by adding the dry weight of leaves-branches and the dry weight of the stem (kg).

Allometric model adjustment and selection

The estimation of the biomass by component (leaves-stem, branches and total) was carried out using logarithmic regression models (Table 1), which were adjusted in accordance with the method of least squares, using the *R Project* statistical package (R Core Team, 2017). The logarithmic transformation is of great utility, since it corrects the heterogeneity of the variance of the independent variable with respect to the data of the dependent variable (Brown *et al.*, 1989). It is necessary to make the transformation, because the variance is highly unstable in arithmetic units, and the logarithmic transformation rectifies the problem (Baskerville, 1972). Six models were evaluated using the following statistics: adjusted coefficient of determination ($_{adj}R^2$), standard error (Syx) and significance of the regression parameters ($P < 0.05$).

Table 1. Models for the estimation of aboveground biomass in *Pinus cembroides* Zucc., and *Pinus halepensis* Mill.

Name	Mathematical function
Natural logarithm	$nl\,B = \beta_0 + \beta_1\ nl\,(ND) + \varepsilon$
Combined Variable	$nl\,B = \beta_0 + \beta_1\ nl\,(ND^2\ H) + \varepsilon$
2nd-degree polynomial	$nl\,B = \beta_0 + \beta_1\ nl\,(ND) + \beta_2\ nl\,(ND)^2 + \varepsilon$
3rd-degree polynomial	$nl\,B = \beta_0 + \beta_1\ nl\,(ND) + \beta_2\ nl\,(ND)^2 + \beta_3\ nl\,(ND)^3 + \varepsilon$
4rd-degree polynomial	$nl\,B = \beta_0 + \beta_1\ nl\,(ND) + \beta_2\ nl\,(ND)^2 + \beta_3\ nl\,(ND)^3 + \beta_3\ nl\,(ND)^4 + \varepsilon$
Generalized variable	$nl\,B = \beta_0 + \beta_1\ nl\,(ND) + \beta_2\ nl\,(H) + \varepsilon$

nl = Natural logarithm; B = Biomass (kg); β_0, ….. ,β_4 = Regression parameters; ND = Normal diameter (cm); H = Total height (m).

Results and Discussion

The *P. halepensis* trees had larger normal diameters and heights than *P. cembroides*; also, there were differences in the biomass of leaves and branches (BLB), the stem biomass (SB) and the total biomass (TB) of 21.8, 38.0 and 59.8 kg, respectively, in *P. cembroides* (Table 2).

Table 2. Dasometric characteristics of the sampled *Pinus cembroides* Zucc., and *Pinus halepensis* Mill. trees.

Species	n	ND		H		BLB		SB		TB	
		Min.	Max	Min.	Max	Min.	Max	Min.	Max	Min.	Max
P. cembroides	50	6.1	11.0	2.9	4.4	7.3	16.0	3.4	14.6	10.8	30.6
P. halepensis	50	6.9	22.8	3.1	6.7	7.8	37.8	7.9	52.6	16.7	90.4

n = Number of trees sampled; ND = Normal diameter (cm); H = Height (m); BLB = Biomass of leaves and branches (kg); SB = Stem biomass (kg); TB = Total biomass (kg); Min = Minimum; Max = Maximum.

Parameters of the adjusted models

Only models 4 and 6 showed no significance (P > 0.05) in the estimation parameters for BLB and TB; the estimation parameters for SB were also not significant in models 3, 5 and 6. Using the same independent variable —normal diameter—, but different models for the total biomass, Díaz *et al.* (2007) and Rodríguez-Ortiz *et al*. (2012) cite smaller parameters than the ones in this study (*P. cembroides),* of β_0 = 0.035 and 0.001 and β_1 = 2.691 and 1.980, respectively, in *P. patula* Schiede ex Schltdl. & Cham. (Table 3).

Table 3. Estimated parameters of allometric models for estimating the biomass in *Pinus cembroides* Zucc.

N°	$β_0$	EE	$β_1$	EE	$β_2$	EE	$β_3$	EE	$β_4$	EE
					Bhr					
1	-1.055	0.24	1.560	0.11	.	.	.	.	.	.
2	-0.916	0.24	0.571	0.04	.	.	.	.	.	.
3	14.005	1.81	-12.775	1.72	3.398	0.40	.	.	.	.
4	46.381*	23.25	-59.239*	33.32	25.539*	15.86	-3.504*	2.50	.	.
5	-1140.09	263.05	2215.13	503.63	1604.52	360.65	514.22	114.49	61.490	13.59
6	-1.058	0.26	1.571	0.31	-0.015*	0.42	.	.	.	.
					Bf					
1	-1.685	0.30	1.799	0.14	.	.	.	.	.	.
2	-1.566	0.28	0.666	0.05	.	.	.	.	.	.
3	-8.103	3.38	7.908	3.21	-1.448*	0.76	.	.	.	.
4	-95.506	42.35	133.347	60.68	-61.223	28.89	9.459	4.57	.	.
5	-153.955*	577.76	245.389*	1106.17	-141.524*	792.12	34.964*	251.45	-3.029*	29.85
6	-1.555	0.31	1.297	0.38	0.712*	0.50	.	.	.	.
					Bt					
1	-0.613	0.15	1.653	0.07	.	.	.	.	.	.
2	-0.484	0.14	0.608	0.02	.	.	.	.	.	.
3	5.078	1.59	-3.764	1.51	1.284	0.35	.	.	.	.
4	-9.265*	20.72	16.821*	29.68	-8.525*	14.13	1.552*	2.23	.	.
5	-655.440	265.67	1255.48	508.64	-896.290	364.23	283.510	115.63	-33.490	13.73
6	-0.558	0.16	1.439	0.19	0.303*	0.26	.	.	.	.

N° = Model number; $β_0$,…,$β_4$= Estimated parameters; EE = Standard error of the parameters.; * = Non-significant parameters.

In *Pinus halepensis*, models 1 and 2 produced parameters with significant differences ($P < 0.05$), compared to the rest of the models, for BLB and TB; as for the SB, the parameters of models 1, 2 and 6 exhibited significant differences ($P < 0.05$), unlike models 3, 4 and 5. Model 2 presented some similarity in the parameters of ($β_1$) 0.444 for BLB, ($β_1$) 0.633 for SB, and ($β_1$) 0.540 for TB (Table 4).

Table 4. Regression parameters of allometric models for estimating the biomass in *Pinus halepensis* Mill.

N°	β_0	SE	β_1	SE	β_2	SE	β_3	SE	β_4	SE
					BLB					
1	0.223	0.31	1.067	0.12	.	.	.	.	.	.
2	-0.061	0.34	0.444	0.05	.	.	.	.	.	.
3	2.598*	2.23	-0.867*	1.80	0.389*	0.36	.	.	.	.
4	15.745*	17.31	-16.878*	20.98	6.821*	8.40	-0.852*	1.11	.	.
5	154.474*	138.17	-243.361*	224.78	144.351*	136.16	-37.669*	36.39	3.666*	3.62
6	-0.013*	0.36	0.938	0.16	0.338*	0.26	.	.	.	.
					SB					
1	-0.759	0.30	1.508	0.12	.	.	.	.	.	.
2	-1.198	0.30	0.633	0.04	.	.	.	.	.	.
3	0.076*	2.16	0.828*	1.75	0.137*	0.35	.	.	.	.
4	-18.522*	16.64	23.478*	20.17	-8.962*	8.08	1.206*	1.07	.	.
5	-197.831*	131.62	316.210*	214.12	-186.721*	129.70	48.792*	34.67	-4.739*	3.45
6	-1.193	0.33	1.272	0.14	0.622	0.23	.	.	.	.
					TB					
1	0.425	0.25	1.292	0.10	.	.	.	.	.	.
2	0.064	0.26	0.540	0.04	.	.	.	.	.	.
3	2.154*	1.80	-0.116*	1.45	0.283*	0.29	.	.	.	.
4	1.070*	14.03	1.205*	17.00	-0.247*	6.81	0.070*	0.90	.	.
5	-8.289*	113.22	16.484*	184.20	-9.525*	111.57	2.554*	29.82	-0.247*	2.96
6	0.094*	0.28	1.112	0.12	0.473	0.20	.	.	.	.

N° = Model number; $\beta_0,\ldots,\beta_4$ = Estimated parameters; SE = Standard error of the parameters; * = Non-significant parameters.

Méndez-González *et al*. (2011) used the same independent variables ($ND^2 \times H$) to predict the TB; their parameters were different from β_0 = 4.660, β_1 = 0.006 for the biomass of leaves and branches, β_0 = 6.183, β_1 = 0.009 for stem biomass, and β_0 = 10.843, β_1 = 0.014 for total biomass in *P. devoniana*. López (2012) pointed out the similarity of the negative values in the origins of ordinate, and positive values in the slopes of BLB and SB in the species that is also the object of the present study (*P. halepensis*); however, the opposite is true for the TB, as both the origin of ordinate and the slope proved to be positive in this study (*P. halepensis*).

Biomass by component in *Pinus cembroides* and *P. halepensis*

Of the six tested models, in the case of *P. cembroides* model 3 was selected because it presented the best statistics for BLB and TB, with an adjusted coefficient of determination ($_{adj}R^2$) above 0.90; on the other hand, the model selected for SB was No. 4 ($_{adj}R^2$ of 0.75), with a mean $_{adj}R^2$ of 0.86 for BLB, SB and TB. However, in the case of *P. halepensis*, model 2 was selected for BLB, SB and TB, with a mean $_{adj}R^2$ of 0.79 (Table 5).

Based on the same model (3) Álvarez (2008) estimated an $_{adj}R^2$ of less than 0.93, as well as an error of 0.67 kg in TB for *Centrolobium tomentosum* Guill. ex Benth. Other studies have cited the same $_{adj}R^2$ of 0.94 for TB, as well as a lower error of 0.33 kg (Schlegel, 2001; Aguirre-Calderón and Jiménez-Pérez, 2011). Using the normal diameter as the independent variable, Xiao and Ceulemans (2004) obtained a better fit and larger error for *P. sylvestris* L. ($_{adj}R^2$ of 0.97, with an error of 2.61 kg), compared to the *P. cembroides* of this study. Méndez-González *et al*. (2011) document a mean R^2 of 0.87 in *P. pseudostrobus*, a value similar to that estimated in this study (for *P. cembroides*).

In the same species (*P. halepensis*) Domingo *et al.* (2016) and López (2012) cite better adjustments, with a higher R^2, of 0.77, 0.94 and 0.89 in BLB, SB and TB, and errors of more than 12.59 kg. Conversely, Návar (2011) documents a lower adjustment of 0.60 and 0.81 for BLB and TB, and a higher adjustment for SB (R^2 0.87), as well as errors of over 9.4 kg, in the species of this study, *P. halepensis*. However, Rodríguez-Ortiz *et al.* (2012) found an error of less than 5.0 kg and an adjustment of more than 0.87 in the TB of *P. patula*. Montero *et al.* (2005) registered a mean $_{adj}R^2$ of 0.85, which represents a higher adjustment than that obtained for *P. halepensis*, with an error of < 0.92 kg.

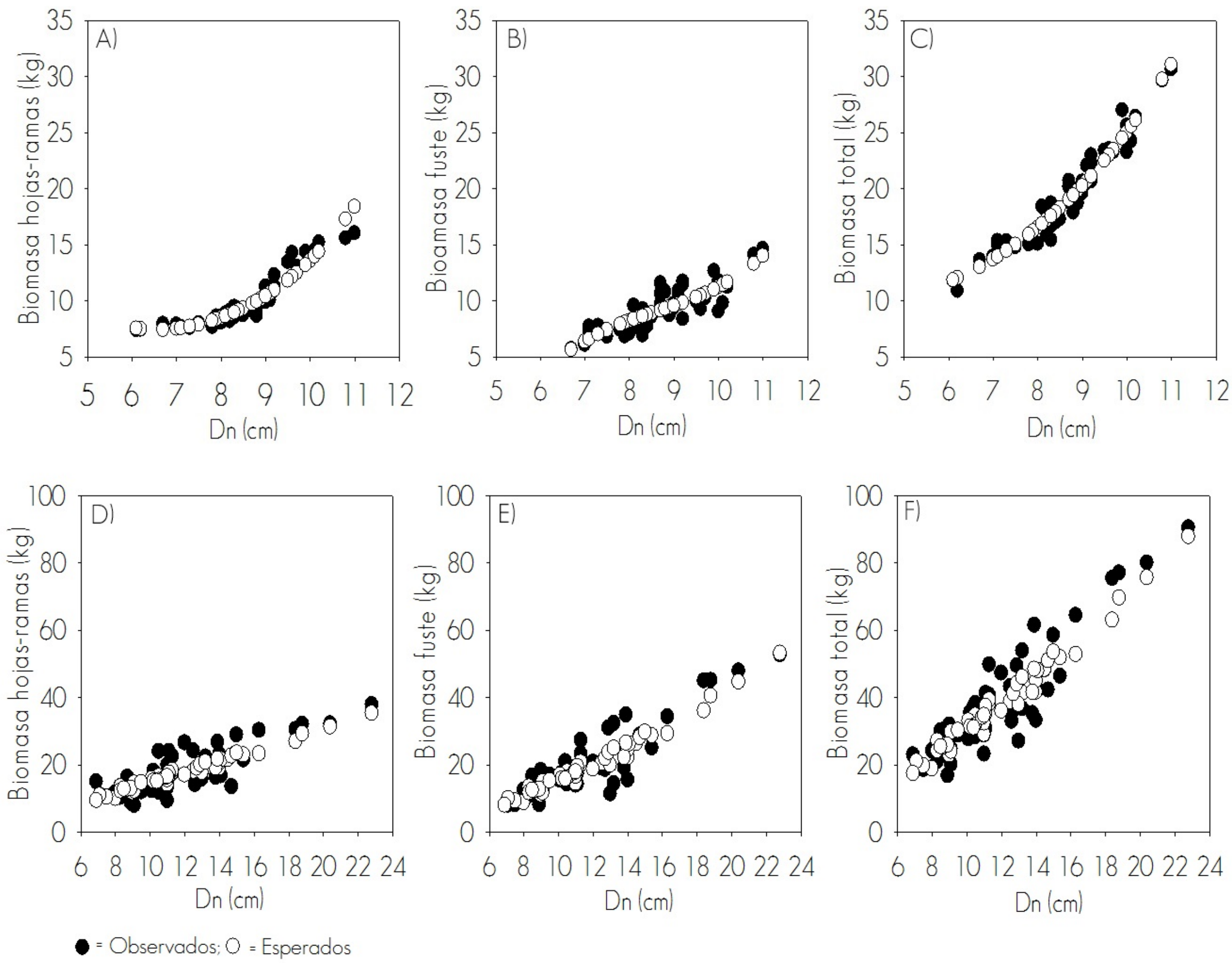
Table 5. Statistical goodness-of-fit of the allometric models for estimating the above-ground biomass in *Pinus cembroides* Zucc. / *Pinus halepensis* Mill.

N°	**Adjusted R^2**	**Syx**	**VC**	**P > F**
		BLB		
1	0.81 / 0.65	1.07 / 4.07	10.58 / 22.24	2.20E-16 / 6.80E-01
2	0.80 / 0.67	1.10 / 3.99	10.86 / 21.81	2.20E-16 / 3.14E-11
3	0.90 / 0.65	0.80 / 4.09	7.88 / 22.35	2.20E-16 / 4.11E-10
4	0.91 / 0.65	0.74 / 4.12	7.33 / 22.50	2.20E-16 / 2.11E-09
5	0.86 / 0.63	0.93 / 4.19	9.21 / 22.91	2.20E-16 / 6.93E-09
6	0.81 / 0.66	1.08 / 4.03	10.69 / 22.00	2.20E-16 / 3.15E-10
		SB		
1	0.74 / 0.81	1.10 / 4.56	12.23 / 21.66	2.20E-16 / 2.2E-16
2	0.75 / 0.85	1.09 / 4.04	12.12 / 19.17	2.20E-16 / 2.2E-16
3	0.74 / 0.81	1.12 / 4.57	12.39 / 21.67	2.20E-16 / 2.73E-15
4	0.75 / 0.79	1.08 / 4.82	11.94 / 22.88	2.20E-16 / 1.45E-14
5	0.75 / 0.81	1.09 / 4.58	12.05 / 21.72	1.79E-15 / 4.52E-14
6	0.74 / 0.85	1.11 / 4.09	12.25 / 19.39	3.21E-16 / 2.2E-16
		TB		

1	0.92 / 0.82	1.23 / 7.14	6.44 / 18.13	2.20E-16 / 2.20E-16
2	0.92 / 0.85	1.25 / 6.50	6.56 / 16.50	2.20E-16 / 2.20E-16
3	0.94 / 0.82	1.07 / 7.09	5.62 / 18.01	2.20E-16 / 8.48E-16
4	0.93 / 0.81	1.10 / 7.18	5.75 / 18.23	2.20E-16 / 8.60E-15
5	0.50 / 0.81	3.03 / 7.23	15.86 / 18.35	2.20E-16 / 6.78E-14
6	0.92 / 0.84	1.24 / 6.59	6.47 / 16.72	2.20E-16 / 2.20E-16

N° = Model number; Syx = Standard Error (kg); VC = Variation coefficient (%); P > F = Significance of the model.

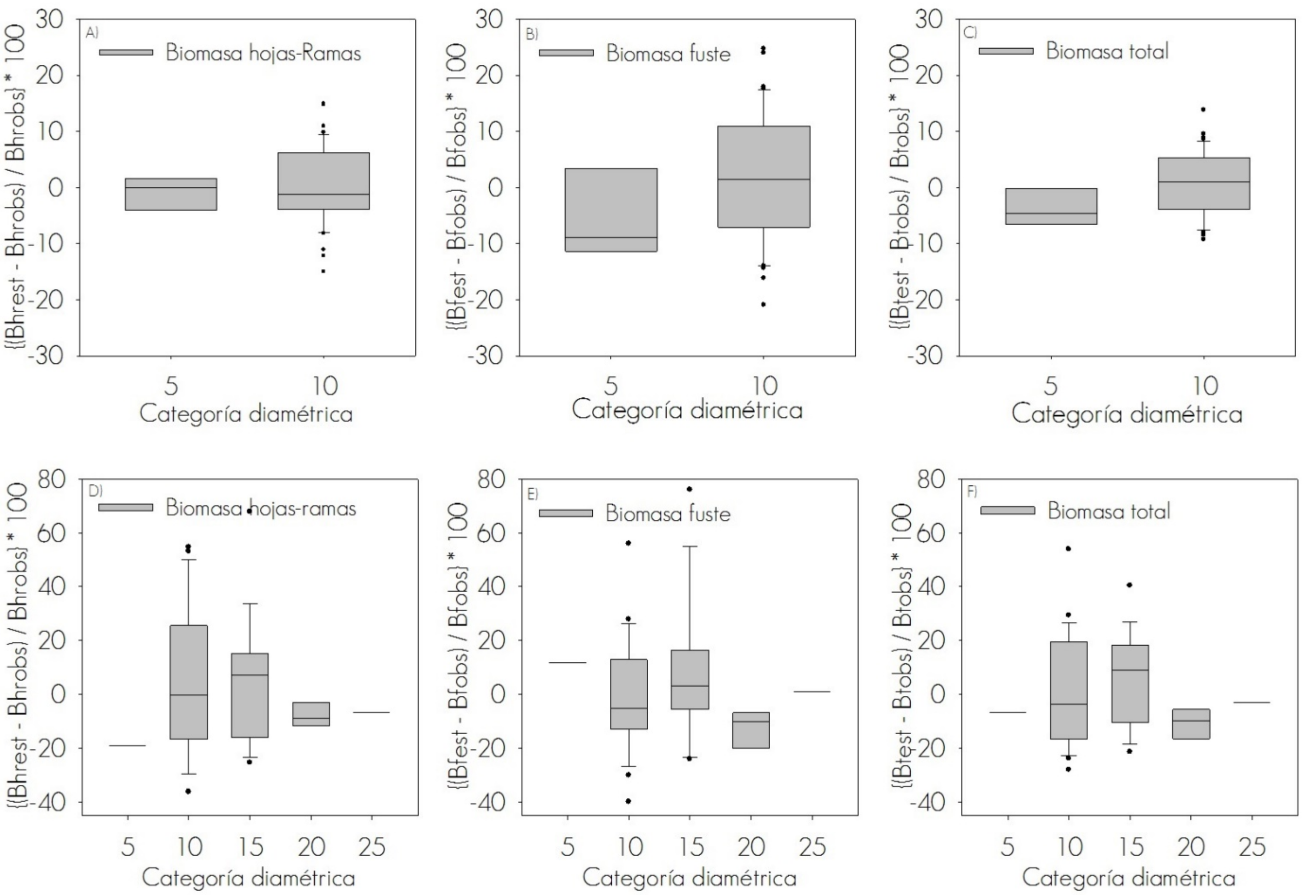
Figures 1A - 1F show the adjustment curves. Among the SB components there was a larger dispersion of estimated values with respect to those observed in *P. cembroides*, due to their variation coefficient (VC) of 11.94 %. While in *P. halepensis* the larger dispersion occurred in the component of BLB, with a VC of 21.81 %. In addition, both species had a lower dispersion in the values for TB.



Biomasa hojas-ramas = Biomass of leaves and branches; *Biomasa fuste* = Stem biomass; *Biomasa total* = Total biomass; *Dn* = DN; *Observados* = Observed; *Esperados* = Estimated

Figure 1. Observed and estimated biomass of leaves and branches, stem biomass and total biomass in trees from a *Pinus cembroides* Zucc. (A - C) and *Pinus halepensis* Mill (D - F) plantation.

Model 3 registered a higher error in the 10 cm category for BLB (Figure 2A), unlike in the 5 cm category for TB (Figure 2C). As for the SB, (Figure 2B) Model 4 had the highest error in the 5 cm category. However, for *P. halepensis*, model 2 obtained a lower error in category 15 of the stem component (Figure 2E) than in the rest of categories. For BLB (Figure 2D) and TB (Figure 2F), the model had lower errors in the 10 cm categories.



Bhr = BLB; *Bf* = SB; *Bt*= TB; *Biomasa hojas-ramas* = Biomass of leaves and branches; *Biomasa fuste* = Stem biomass; *Biomasa total* = Total biomass; *Categoría diamétrica* = Diameter category; *est* = Estimated; *obs* = Observed

P. cembroides: BLB and TB = Biomass estimated with Model 3; SB = Biomass estimated with Model 4; *P. halepensis*: BLB, SB and TB = Biomass estimated using model 2.

Figure 2. Percentage error of estimation of the biomass per component in each diameter category of *Pinus cembroides* Zucc. (A - C) and *P. halepensis* Mill (D - F).

Conclusions

The indirect (Adelaide) method is a good estimator of above-ground biomass; with this method, the best adjustments of the models were found to be related to the total biomass. In *Pinus cembroides*, the normal diameter adequately predicts the biomass; conversely, in the case of *P. halepensis* it is necessary to have two independent variables: normal diameter and height. Data regarding the biomass of leaves and branches, stem biomass and total tree biomass, as well as of the biomass per stand, can be obtained using the adjusted models (combined variable, polynomial of 2^{nd} and 3^{rd}-degree), in order to estimate the stored carbon and carbon dioxide. The models with percentage errors in the diameter categories underestimate the biomass.

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Conflict of interest

The authors declare no conflict of interest.

Contribution by author

Paul Marroquín Morales: planning and development of the research; data collection, processing and capture; statistical analyses; drafting and structuring of the manuscript; Jorge Méndez González: statistical analyses and review of the structure of the manuscript; Javier Jiménez Pérez: review and structuring of the manuscript; Oscar Alberto Aguirre Calderón: structuring and review of the manuscript; José Israel Yerena Yamallel: review of the manuscript.