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Article

Factores de expansión y sistema de partición de biomasa aérea para *Pinus chiapensis* (Martínez) Andresen

Expansion factors and system partition of aerial biomass for *Pinus chiapensis* (Martínez) Andresen

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Resumen:

En el presente estudio se desarrollaron factores de expansión para biomasa constante y variable, además de un sistema de partición de biomasa aérea en plantaciones forestales comerciales de *Pinus chiapensis.* Mediante un muestreo destructivo de 35 árboles, se obtuvo el peso fresco de fuste, ramas y follaje en el campo y se tomaron muestras para determinar su peso seco. La relación del peso seco y fresco se empleó para convertir el peso freso en biomasa. A partir de una proporción directa del volumen total del fuste multiplicada por un factor de expansión de biomasa constante se estimó la biomasa aérea. El factor de expansión de biomasa variable se determinó con base en el cociente del modelo de biomasa aérea total y del volumen total del fuste. El sistema de partición de biomasa aérea se ajustó como una función directa de la biomasa y un factor de partición, que define la proporción de la biomasa por componentes. El valor del factor de expansión de biomasa constante reveló que por cada metro cúbico existen 709 kg de biomasa. El sistema de partición de biomasa aérea indicó una distribución de biomasa mayor en el fuste con 69 %, de ramas con 21 % y de follaje con 10 %. La aplicación de los factores de expansión de biomasa y sistema de partición de biomasa aérea permiten calcular la biomasa aérea total y por componentes a partir del volumen total del fuste de los árboles medidos en los inventarios forestales.

Palabras clave: Biomasa forestal, componentes estructurales, ecuaciones alométricas, *Pinus chiapensis* (Martínez) Andresen, plantaciones forestales, volumen total fuste.

Abstract:

In the present study, expansion factors for constant and variable biomass were developed, as well as an aerial biomass partition system in commercial forest plantations of *Pinus chiapensis*. By means of a destructive sampling of 35 trees, the fresh weight of stems, branches and foliage in the field was obtained and samples were taken to determine their dry weight. The ratio of the dry and fresh weight was used to convert the green weight into biomass. The aerial biomass was estimated from a direct proportion of the total volume of the stem multiplied by a constant biomass expansion factor. The variable biomass expansion factor was determined based on the quotient of the total aerial biomass model and the total volume of the stem. The aerial biomass partition system was fitted as a direct function of the biomass and a partition factor, which defines the proportion of the biomass by components. The value of the constant biomass expansion factor revealed that for each cubic meter there are 709 kg of biomass. The system of aerial biomass partition indicated a greater biomass distribution in the stem with 69 %, of branches with 21 % and of foliage with 10 %. The application of the biomass expansion factors and the aerial biomass partition system allow us to calculate the total aerial biomass and by components from the total stem volume of the trees measured in the forest inventories.

Keys words*:* Forest biomass, structural components, allometric equations, *Pinus chiapensis* (Martínez) Andresen, forest plantations, total stem volume.

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Introduction

The biomass expansion factors and the aerial biomass partition system are reliable tools for estimation in native forests and commercial forest plantations. Aerial biomass plays an important role in the sustainable management of forest resources and in the quantification of carbon dioxide (CO_2) stores (Zhang *et al.,* 2017); in addition, it is an important measure to analyze productivity, evaluate the amount of nutrients and the CO_2 cycle (Aosaar *et al.,* 2016).

In this context, native forests and commercial forest plantations play an important role in mitigating climate change, through the sequestration of carbon dioxide (Zheng *et al.,* 2015). The amount of biomass contained in a tree is influenced, mainly, by the type of ecosystem where the species develop, such as the annual average rainfall and temperature, age, density, potential productivity of the site and the forestry used, which makes it necessary to generate information at the taxon level (Poudel and Temesgen, 2016).

The estimation of the total aerial biomass at the tree level starts with a destructive sampling, and is one of the most precise methods that consists in the direct measurement of each one of the components: stem, branches and foliage, but due to its high cost and time required, its application is limited to a small sample (Addo and Rahmad, 2013). However, the information derived from this type of measurement allows the development of non-destructive indirect methods, for example: i) the allometric equations developed by linear and non-linear regressions, which estimate biomass based on normal diameter and total height (Rodríguez *et al*., 2012); ii) the basic density of the wood, which by multiplying the density by the estimated volume in individual trees calculates the biomass (Ordóñez *et al*., 2015) and iii) the biomass expansion factor, which multiplies the estimated volume of individual trees by a conversion factor of m^3 to kg (Magalhães and Mate, 2018).

Currently, a large part of the research focused on biomass estimation focuses on equations with simple mathematical structures; for example, those that relate an independent variable, such as the normal diameter (Acosta *et al.,* 2011; Carrillo *et al*., 2016); the complex equations that allow a better description of the distribution pattern of the biomass, in this group are those that relate two or more independent variables: normal diameter, total height, clean bole height, diameter of live crown and the basic density of wood (Djomo and Chimi, 2017; Hernández *et al*., 2017).

A rapid, applicable, reliable and frequently used method for calculating indirect values of biomass from volume is based on biomass expansion factors. The application of these is important because most of the forest inventory information related to the volume is easily estimated based on the normal diameter and total height, which makes it easy to convert the estimated volume into individual trees with a conversion factor of m^3 to kg (Magalhães and Mate, 2018).

Indirect methods allow non-destructive estimation of biomass for large areas through information derived from forest inventories of sites with fixed or variable dimensions; however, to know the proportion of biomass of stem, branches and foliage with respect to the total aerial biomass it is necessary to generate a system of biomass partition for individual trees of the following form:

$$\lambda_i \times B_T,$$

Where:

λ = Components ratio

B_T = Total aerial biomass

The assumption is that the additivity is guaranteed and that the sum of the components is equal to the total aerial biomass (Aquino *et al*., 2015).

The investigations described have allowed to estimate with precision the total aerial biomass and by components, but there are few studies cited in the literature for *Pinus chiapensis* (Martínez) Andresen. The most similar are those developed by Chávez-Pascual *et al*. (2013), who estimated the total aerial biomass by biomass expansion factors in natural stands of this species in the community of *San Juan Tabaá* of the *Sierra Norte de Oaxaca.*

Estimates of total aerial biomass in commercial forest plantations of *P. chiapensis* are crucial to assess their potential in CO_2 sequestration; it is also a parameter of national and international interest due to its impact in mitigating the effects of climate change; therefore, first reliable statistical tools are required to estimate the total aerial biomass. Therefore, the objective of this study was to develop constant and variable biomass expansion factors, as well as a partition system to estimate the total aerial biomass and components in commercial forest plantations for *P. chiapensis*, in *Tlatlauquitepec*, *Puebla*.

Materials and Methods

Study area

The research was carried out in 87 ha planted with *P. chiapensis*, established in *El Campanario*, located in the town of *Chicuaco, Tlatlauquitepec* municipality, *Puebla* (Figure 1). The information comes from 35 trees sampled and felled in 2014, systematically distributed in ages of 3 to 7 years. These plantations are located between 19°46’10.6’’ N and 97°28’34.6’’ W. The plants come from seeds of selected trees of the region, produced in three certified forest nurseries: *Mazatepec (Tlatlauquitepec), Esperanza de la Mañana* (*Cuetzalan*) and *Atoluca (Teziutlán*); they were placed on land that was previously used for fruit and coffee production (Fierros *et al*., 2018).

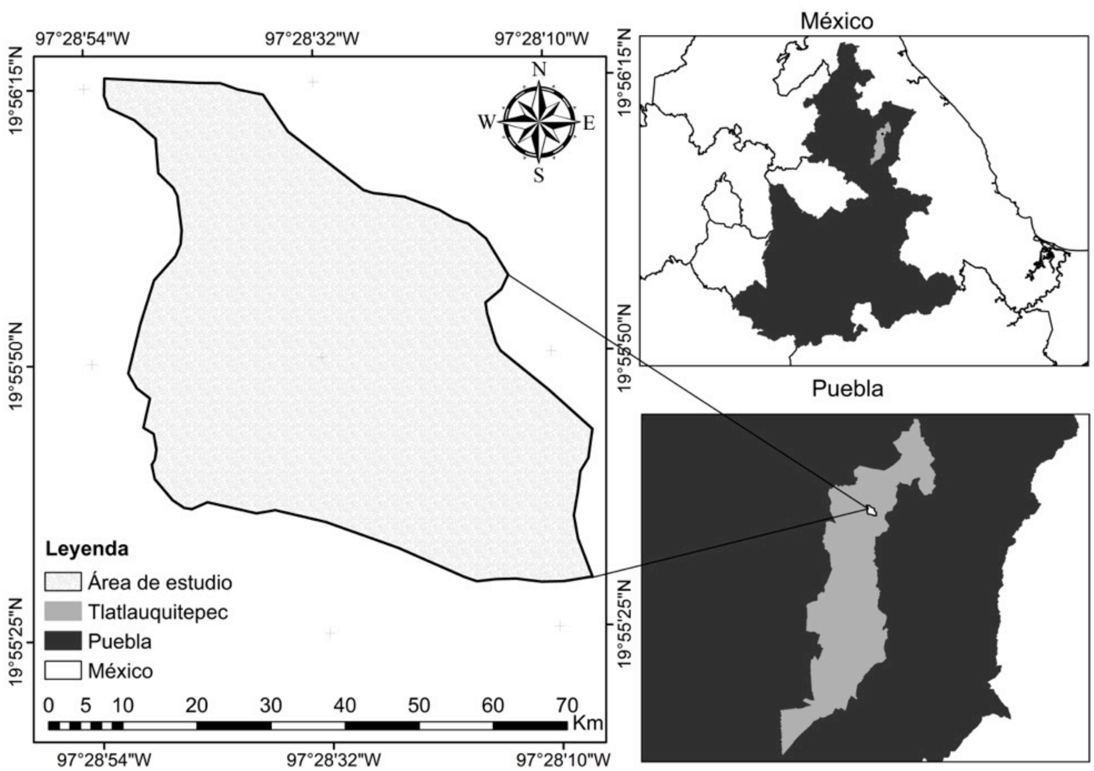

Figure 1. Location of the study area.

The plantation (PFC) was established at a density of 1 100 trees ha^{-1}, in real frame with a spacing of 4 m between rows and 2.25 m between plants. The climate is semi-warm humid with rain throughout the year, with an average annual temperature of 17 °C and average annual precipitation of 2 350 mm. The predominant soils in *Tlatltauquitepec* are Andosol with 68 %: Acrisol with 12 %; Phaeozem with 5.5 % and Leptosol with 2 % (Inegi, 2009).

Biomass sampling by components

With the direct methodology, 35 trees of *P. chiapensis* of different ages (3, 5, 6 and 7 years old) were sampled in 2014, for which individuals without physical damage were selected and that covered all the categories of diameters and heights. The felling took place at 5 cm above ground level; subsequently, each tree was measured the following variables: total height (H in m measured with a 30 m Truper measuring tape) and normal diameter (D in cm measured with a 50 cm Haglof Mantax Blue caliper).

In the felled individuals the stem, the branches and the foliage were separated, then the bole was sectioned, the first log was cut to 1.20 m in length and the rest to 2.40 m until reaching the tip of the tree, the weight was recorded in green (kg), with a 120 kg Oken platform scale model K-1. For the first log, two slices were obtained (lower and upper) and for the others only the upper one, with an average of 5 cm in thickness, noting the diameter with bark (DCC, for its acronym in Spanish) and the weight in green (kg) with a scale Torrey® electronics L-EQ-10 series, 10 kg. For the total green weight of the branches and foliage, random samples of 1 kg and 1/2 kg of branches and foliage were taken, respectively. In the laboratory the dry weight was determined by components, after being dried in a Sheldon model 1675-S kiln, at 75 °C, until constant dry weight was achieved.

Estimation of biomass by component

Biomass was estimated for stem (B_F), branches (B_R) and foliage (B_H), based on the methodology suggested by Repola and Ulvcrona (2014) as a function of the ratio estimator (*r*), in the dry weight ratio (*ps*) and the green weight (*pv*) of the samples of the components. The estimator of *r* was used to convert the total green weight by components (PV_i) to biomass. B_F, B_R and B_H were calculated using equation (1):

$$B_i = PV_i \times r \qquad (1)$$

Where:

B_i = Biomass per components

PV_i = Total green weight per components

r = Ratio estimator

Constant and variable biomass expansion factor

The total aerial biomass can be estimated by a constant or variable biomass expansion factor (FEB), by converting the volume (V in m^3) to biomass (B_T in kg). Therefore, it is assumed that the V is a direct linear function of $D^2 \times H$, this makes it possible to calculate the total aerial biomass as a direct ratio of the total volume of the plant multiplied by a constant FEB with the equation (2) (Hernández *et al.*, 2017):

$$B_T = \vartheta \times V \qquad (2)$$

Where:

B_T = Total aerial biomass (kg)

ϑ = Constant FEB

V = Total volume of the stem (m^3) estimated with the Schumacher and Hall type volume equation (1933), generated for the same species studied and plantation by Martínez (2016)

The V function presented an adjusted coefficient of determination value (R^2_{adj}) of 99.66 % and root mean square error (RMSE) of 0.0058. The V was estimated by equation (3):

$$V = 0.000065 \times D^{1.630512} \times H^{1.15635} \qquad (3)$$

Where:

V = Total volume of the stem (m^3)

D = Normal diameter (cm)

H = Total height (m)

From the above reasoning, generating a variable FEB may be more realistic than a constant FEB, since the latter assumes, precisely, that the proportion of biomass remains constant, which is not completely true, because at different ages and site quality, the FEB presents a significant differential variation in a tree (Enes and Fonseca, 2014). The variable FEB is a way to analyze how the biomass varies depending on the size (D and H) of the tree, and one way to generate it is from the relation of the equation (5) of total aerial biomass generated for the same species and plantation studied by Martínez (2016), in which the function of total aerial biomass presented an adjusted coefficient of determination value (R^2_{adj}) of 98.44 % and root mean square error (RMSE) of 9.44 and equation (3), as expressed in the general equation (4) (Pajtík *et al.,* 2008).

$$\text{FEB} = \frac{B_T}{V}\left[\frac{kg}{m^3}\right] = \frac{\alpha_1 X^{\beta_1}}{\alpha_2 X^{\beta_2}} = \alpha D^{\beta} \qquad (4)$$

Where:

$$\alpha = \frac{\alpha_1}{\alpha_2}$$

$$\beta = \beta_1 - \beta_2$$

$$B_T = 0.128525 \times (D^2 H)^{0.80311} \qquad (5)$$

Where:

FEB = Variable biomass expansion factor

α_i, β_i = Parameters of the B_T y V equations

B_T = Total aerial biomass (kg)

V = Total stem volume (m^3)

The total aerial biomass is obtained by multiplying the constant and variable FEB by the estimated V for each tree measured in forest inventories, by means of equation (6) (Magalhães and Seifert, 2015):

$$B_T = FEB \times V \quad (6)$$

Where:

B_T = Total aerial biomass (kg)

FEB = Biomass expansion factor

V = Total stem volume (m^3)

Aerial biomass distribution partition system

Although the estimation of the FEB allows estimating the total aerial biomass derived from a forest inventory (Magalhães and Seifert, 2015), the distribution of the biomass by components of the individuals coming from a *P. chiapensis* plantation under management is still unknown. Therefore, an aerial biomass partition system was generated by the expression (7):

$$B_i = \lambda_i \times B_T \quad (7)$$

Where:

B_i= Biomass per components

λ_i = Biomass per components ratio in regard to B_T

B_T = Total aerial biomass (kg)

To know the distribution of the biomass in the tree components, a direct function of the total aerial biomass and a partition factor λ_i,was adjusted, as indicated in equation (8) (Aquino *et al.,* 2015):

$$B_i = f_i \times (\lambda_i, \mathrm{B}_T) + \varepsilon \qquad (8)$$

Where:

B_i= Biomass per components

f_i= Function that defines the biomass of the components

λ_i = Ratio of the biomass per components in regard to B_T

B_T = Total aerial biomass

ε = Random error

From which a system of equations is derived as follows:

$$B_F = g(\lambda_1, B_T) + \varepsilon \qquad (9)$$

$$B_R = ☒(\lambda_2, B_T) + \varepsilon \qquad (10)$$

$$B_H = i(\lambda_3, B_T) + \varepsilon \qquad (11)$$

Where:

B_F = Stem biomass

B_R = Branch biomass

B_H = Foliage biomass

B_T = Total aerial biomass

$g(\lambda_1, B_T)$, $h(\lambda_2, B_T)$, $i(\lambda_3, B_T)$ = Functions that define the biomass of the components

ε =Random error

λ_i = Vectors of the parameters used in the adjustment indicate the ratio of the biomass of the components

Therefore, the additivity is guaranteed with the linear restrictions on the regression coefficients, in such a way that the sum of the biomass of the components is equal to the total aerial biomass, by means of equation (12) (Parresol, 2001):

$$B_T = B_F + B_R + B_H = \{[g(\lambda_1, B_T) + \varepsilon] + [h(\lambda_2\,, B_T) + \varepsilon] + [i(\lambda_3, B_T) + \varepsilon]\} \quad (12)$$

Fitting methods of the models

The fit of the variable expansion factor and the aerial biomass partition system were made with the SUR method or Seemingly Unrelated Regressions (SAS, 2011). The SUR procedure homogenized and optimized the standard error of the parameters; with this, the complete compatibility in the aerial biomass partition system was obtained, and a lower variance was generated as well as efficient results in the predictions (Parresol, 2001).

Results and Discussion

Characteristics of the forest attributes of *Pinus chiapensis*

The normal diameter of the sampled trees was recorded in a range of 3.20 to 26.50 cm, total height of 4.25 to 17.05 m and total aerial biomass 2.46 to 220.52 kg (Table 1). The stem was the component with a large increase in the proportion of biomass by increasing the diameter and total height. The validity of the factors of expansion of biomass and the system of participation of aerial biomass are restricted to the minimum and maximum values of the dasometric variables, this implies that they can only be applied for the species studied and for the same region.

Table 1. Forest attributes of the trees sampled.

Variables	N	Mean	Minimum	Maximum	SD
Normal diameter (cm)	35	15.20	3.20	26.50	6.76
Total height (m)	35	11.08	4.25	17.05	3.79
Stem biomass (kg)	35	59.89	1.10	157.99	48.27
Branch biomass (kg)	35	18.92	0.48	47.40	14.53
Foliage biomass (kg)	35	8.62	0.72	20.99	6.23
Total aerial biomass (kg)	35	87.44	2.46	220.52	68.62
Age (years)	35	5.63	3.00	7.00	1.52

N = Number of observations; SD. = Standard deviation.

Constant biomass expansion factor

The results of the constant FEB adjustment statistics showed a value of 97.51 % in the adjusted coefficient of determination (R^2_{adj}) and an average error of 10.9183 kg in the root of the mean square of the error (RMSE). The value of the estimator of the parameter θ showed high significance (p <0.0001). So the equation (2) to estimate the total aerial biomass as a function of a constant FEB (ϑ) is as follows:

$$B_T = 709.8016 \times V \qquad (2)$$

Where:

B_T = Total aerial biomass

V = Total volume of the stem with bark (m^3)

The estimated value of the parameter ϑ representing the constant FEB was 709.8016, which suggests that for each m^3 there are 709 kg of total aerial biomass in *P. chiapensis.*

In conifers, dry stem biomass and stem volume have an approximately constant FEB of 500 kg m^3; the difference of this value gives an idea of the proportion of branches and leaves. With the focus of this study, Cruz (2007) estimated, in managed forests of *Zacualtipán*, *Hidalgo*, a value of 623.2698 kg m^3 for *Pinus teocote* Schltdl. & Cham; while, for hardwoods: *Liquidambar macrophylla* Oerst., *Quercus* spp, *Clethra mexicana* D.C., *Prunus serotina* Ehrh ssp. *capuli* (Cav.) Mc Vaugh, *Alnus jorullensis* Kunth subsp. *lutea* Furlow, *Carpinus caroliniana* Walter and *Viburnum ciliatum* Greenm., the estimated FEB was 905.1358 kg m^3. The author reported a greater proportion of branch biomass with respect to stem biomass.

Something similar arises Aquino (2014) with FEB values of 1 358.5 and 998.56 kg m^3 for the tropical species *Cupania dentata* DC., *Alchornea latifolia* Sw. and *Inga punctata* Willd, respectively. In the work done by Chávez-Pascual *et al*. (2013) reported an average FEB of 443.53 for *P. chiapensis*, in natural stands in the *Sierra Norte de*

Oaxaca under forest exploitation. The authors point out that the branch and foliage biomass represented 7.5 % of the total aerial biomass, while in this study it was 31 % and an FEB of 709.9016.

Undoubtedly, variations in branch and foliage biomass are more influenced by young ages, physiological and morphological functions, and applied silvicultural practices (weed control and pruning) to *P. chiapensis* trees. The latter as those observed during the data recording: at ages 3 to 7, all trees were pruned and vegetation control measures were observed, which leads to the development of wide and well-shaped crowns. Fierros-Mateo *et al*. (2017) documented for the same plantation that silvicultural treatments such as pruning and weed control applied to the mass of *P. chiapensis* at an early age (first year after planting) give rise to high growth rates, and, consequently, a robust development of crowns that allow a greater photosynthetic efficiency for the transformation to aerial biomass.

Variable biomass expansion factor

The variable FEB expressed by equation (13) was obtained by substituting the values of the parameters of the total aerial biomass equation and the total stem volume by the expression (4):

$$\text{FEB}=\frac{B_T}{V}\left[\frac{kg}{m^3}\right]=\frac{0.128525\times\left(D^2H\right)^{0.80311}}{0.000065\times \text{D}^{1.630512}\times \text{H}^{1.15635}} \quad (4)$$

$$FEB = 1977.30769231 \times (D^{-0.024292}H^{-0.35324}) \quad (13)$$

With the equation (13) it is possible to observe how the variable FEB is modified according to the dimensions of the trees (Figure 2), which leads to more accurate biomass predictions (Chávez-Pascual *et al.,* 2013), since they reflect indirectly changes the proportion of the components.

The variable FEB by diametric category refers to the changes in the balance of the stem biomass with respect to branch and foliage biomass. As the D and H increases the biomass increases, but the variable FEB tends to stabilize in diameter categories (CD) of 20 cm of D and H of 15 m, since the shaft of the tree begins to concentrate a greater biomass possibly in this stage, the level of contribution of the branch to the total biomass of the tree is stabilized and the percentage of foliage continues to decrease. It is likely that this is related to limited light resources under closed canopy conditions and as a consequence the limitations for foliage survival (Konôpka *et al*., 2015). Silva and Návar (2010) and Chávez-Pascual *et al*. (2013) indicated the same variation, because variable FEBs are dependent on tree dimensions, such as D and H.

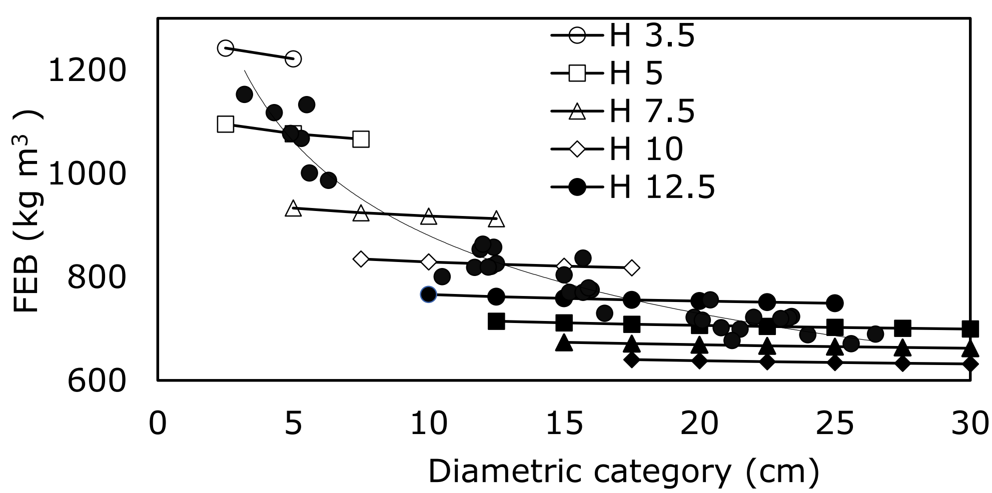

Figure 2. Expansion factors of variable biomass by diametric categories and sampled heights, estimated from the equation 15.

Such behavior is similar to that described by Chávez *et al*. (2013) for natural stands under management of *P. chiapensis* in the *Sierra Norte de Oaxaca*, and as recorded by Hernández *et al*. (2017) for *Eucalyptus urophylla* S. T. Blake in commercial forest plantations aged 1 to 7 years in *Humanguillo, Tabasco*.

Enes and Fonseca (2014) recorded a similar tendency of variable FEB for natural stands of *Pinus pinaster* Ait in the North of Portugal. According to Konôpka *et al*.

(2015), the variable FEB decreases progressively as a contribution of tree components that changes with the increase in tree size (D and H), in which a significant change is observed for smaller individuals.

Undoubtedly, these changes obey the strategy of changing growth from early stages (where the first intention is to occupy enough space on the ground) to later ones (to compete with neighboring trees for light). Pajtík *et al.* (2008) mention that the amount of light captured by the canopy in the young trees is 100 % and the branches, therefore, represent more branch biomass, which explains a higher variable FEB. However, after the canopy closes, the proportion of branch biomass decreases significantly along with the amount of light that is intercepted by the canopy; in consequence, the variable FEB, because the stem begins to concentrate more biomass.

Figure 3 shows that the total aerial biomass calculated with the variable biomass expansion factor is more conservative, according to the trend of total aerial biomass observed.

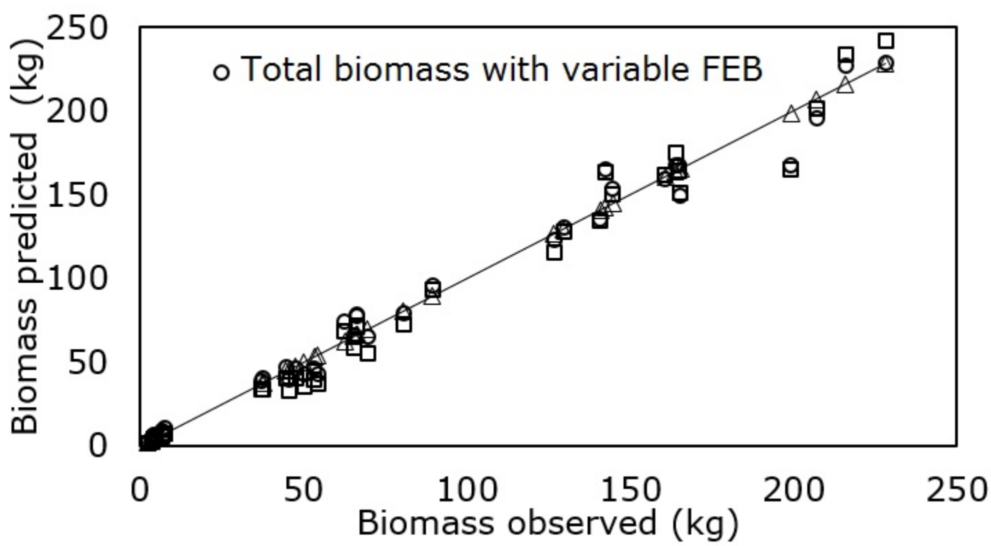

Figure 3. Relation of the total aerial biomass predicted with the constant and variable FEB as a function of the observed total aerial biomass (kg).

For future studies in the plantations it will be very difficult to directly obtain the total aerial biomass; therefore, it is suggested to use the variable biomass expansion factor since it provides greater reliability, with the purpose of estimating total aerial biomass indirectly for trees measured in forest inventories.

Biomass partition systems

Table 2 summarizes the goodness of fit statistics of the biomass partition system: root mean error square (RMSE), adjusted coefficient of determination ($R^2_{adj.}$) and parameter estimators. The results indicated that the stem biomass showed the highest value in the $R^2_{adj.}$ with 99.56 %, followed by the foliage biomass with 97.28 % and finally the biomass of branches with 96.37 %.

The independent variables of D and H were well adjusted to the biomass data, explaining a variation greater than 96 % for the prediction of the biomass by components. While, the values in RMSE were 3.21, 2.76 and 1.02 for biomass of stem, branches and foliage, respectively. The γ_i parameters are highly significant in the hypothesis test, given that their associated probability is less than the 5 % level of significance (α = 0.05). The γ_i values represent the proportion of biomass per component, with respect to the total aerial biomass.

Table 2. Adjustment statistics, values and significance of the parameters of the aerial biomass partition system.

Components	**RMSE**	R^2_{adj}	ρ	**Ψi**	**∞**
Stem	3.2101	0.9956	γ_1	0.691336	<0.0001
Branches	2.7675	0.9637	γ_2	0.213308	<0.0001
Foliage	1.0285	0.9728	γ_3	0.095355	<0.0001

ρ = Parameter of the aerial biomass partition system; Ψ = Value of the estimators of the parameters; ∞ = Significance level of the estimators of the parameters.

The values of γ_i indicate that the highest accumulation of biomass is concentrated in the stem with 69 %, followed by 21 % in branches and 10 % for the biomass of the foliage (Table 3). These results are similar to those of Soriano *et al*. (2015) with the biomass proportions for *Pinus patula* Schiede ex Schltdl. *et* Cham.: stem (68.2 %), branches (14.3 %), foliage (8.2 %) and bark (9.3 %), which is explained by the fact that both species have partial (rapid) growth rates and share mesophilous forest habitats.

Martínez *et al*. (2016) determined 81 % for trunk, 14 % branches and 5 % foliage in *P. ayacahuite* var *veitchii* Shaw in natural stands of *Ixtlán, Oaxaca*. This distribution differs from the cited studies reported by Rodríguez *et al.* (2012) for a 14 years plantation of *P. patula*, whose proportion of stem biomass was 92.9 %, of branches of 4.7 % and foliage of 2.4 %. The above shows that the foliage proportion of *P. patula* has greater photosynthetic efficiency with respect to *Pinus chiapensis*. However, it can also be attributed to the thinnings made in the plantation, which generated more concentration in stem biomass. This agrees with the studies of Chávez-Pascual *et al*. (2013), who registered distributions of stem biomass of 92.5 %, branches with 6.3 % and foliage with 1.2 % for stands of *P. chiapensis* under management.

The distribution of biomass from tropical climate species such as *Cupania dentata* DC., *Alchornea latifolia* Sw. and *Inga punctata* Willd. contrasts with conifers since they present, generally, a greater concentration of biomass of branches and foliage (54.32, 50.58, 59.26 %, respectively) than in stem biomass (40.69, 38.53, 33.65 %, respectively) (Aquino *et al*., 2015).

A system of equations for individual trees was formed in the following way: equation (6) calculates the total aerial biomass at the tree level, which multiplies the variable biomass expansion factor (13) by the total stem volume (3).

$$FEB = [1977.30769231 \times (D^{-0.024292} H^{-0.35324})] \quad (13)$$

$$V = 0.000065 \times D^{1.630512} \times H^{1.15635} \quad (3)$$

$$B_T = FEB \times V \quad (6)$$

Then, once the total aerial biomass is estimated, it is possible to know the proportion by components, by substituting the values γ_i estimated in the aerial biomass partition system, by means of expressions 9, 10 and 11. With this system the additivity is fulfilled (12), also allows to build a table of yield of total aerial biomass and by components, based on the D and H (Table 3).

$$B_F = 0.691336 \times B_T \quad (9)$$

$$B_R = 0.211336 \times B_T \quad (10)$$

$$B_H = 0.095355 \times B_T \quad (11)$$

$$\mathrm{B}_T = B_F + B_R + B_H \quad (12)$$

Table 3. Distribution of total aerial biomass and by components, for each category of normal diameter and total height.

	Height category																			
CD	B_F	B_R	B_H	B_T	B_F	B_R	B_H	B_T	B_F	B_R	B_H	B_T	B_F	B_R	B_H	B_T	B_F	B_R	B_H	B_T
	5	**5**	**5**	**5**	**10**	**10**	**10**	**10**	**15**	**15**	**15**	**15**	**20**	**20**	**20**	**20**	**25**	**25**	**25**	**25**
5	4	1	1	6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
10	-	-	-	-	23	7	3	33	32	10	4	46	-	-	-	-	-	-	-	-
15	-	-	-	-	44	13	6	63	61	19	8	88	76	24	11	110	-	-	-	-
20	-	-	-	-	-	-	-	-	96	30	13	139	121	37	17	175	145	45	20	210
25	-	-	-	-	-	-	-	-	-	-	-	-	173	53	24	251	207	64	29	300
30	-	-	-	-	-	-	-	-	-	-	-	-	232	72	32	336	278	86	38	402

B_F = Stem biomass; B_R = Branch biomass; B_H = Foliage biomass; B_T = Total aerial biomass; CD = Diametric category; - = No values exist.

Conclusions

The biomass expansion factors generated to estimate the total aerial biomass in the commercial forest plantations of *Pinus chiapensis* include easy-to-measure predictive variables in the forest inventories, such as the normal diameter and total height, which facilitates converting the total volume to total aerial biomass. The system of aerial biomass partition equations guarantees additivity and generates more precise estimates. With this system it is possible to calculate the biomass by components from the information generated in the forest inventories, which is fundamental to transform the biomass to carbon captured in the plantations of *P. chiapensis.*

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Conflict of interests

The authors declare no conflict of interests.

Contribution by author

Luis Martínez Ángel: data analysis and writing of the original manuscript; Héctor Manuel De los Santos Posadas: design of the study; Aurelio Manuel Fierros González: development of the methodology; Ramiro Pérez Miranda: development of the methodology; Reynol Fierros Mateo: review of the original manuscript; Adrián Hernández Ramos and Jonathan Hernández Ramos: review of the final manuscript.

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