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Biomass assessment, volume equations and crown architecture of *Eucalyptus pellita* F. Muell in a commercial plantation in Mexico

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Abstract

A fixed number of 6 trees from a provenance study were selected at random in a commercial plantation of *Eucalyptus pellita*, from different diameter classes. Each tree was separated by components: stem, leaves, branches, which were then weighed to obtain green weight. Linear regressions were carried out to obtain straight forward biomass models for the aerial component, using DBH as the independent variable. Later corresponding analyzes were performed to obtain the amount of carbon (C) and carbon dioxide (CO_2) stored in a 2.5 year old plantation. Overall, we obtained an average of 27.04 kg of carbon stored in the stem and 10.44 kg of carbon in the foliage, which represents a reservoir of 99.23 kg of CO_2 stored in the stem and 38.32 kg of CO_2 in the foliage. In literature, not many studies are found on crown development; the present

Resumen

En un ensayo de procedencia se seleccionaron seis árboles de *Eucalyptus pellita* F. Muell, de diferentes clases de diámetro; para obtener el peso verde en campo cada árbol fue separado en sus componentes: tallo, hojas, ramas. Se llevaron a cabo regresiones lineales para obtener modelos de biomasa para el componente aéreo, utilizando el diámetro a la altura del pecho (DAP) como la variable independiente. Posteriormente se realizaron análisis para obtener la cantidad de carbono (C) y el dióxido de carbono (CO_2) almacenado en una plantación de 2.5 años de edad. En general, se obtuvo un promedio de 27.04 kg de carbono almacenados en el tallo y 10.44 kg de carbono en el follaje, que representa un reservorio de 99.23 kg de CO_2 almacenados en el tallo y 38.32 kg de CO_2 en el follaje. En la literatura, no hay muchos estudios sobre desarrollo de copa; el presente trabajo relaciona

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study relates crown height, crown diameter and total height into 4 indexes which describe a given structure of the tree (Crown Coverage (CC), Crown Index (CI), Crown Shape (CS), Crown Shade (CSd)). The results show, for the six sampled individuals, a relatively high value for CC, showing the lowest value for the smallest diameter; crown coverage indicates that the species at this age class is still growing rather exponentially and that its photosynthetic area needs still to be high to sustain such growth. Concerning crown shape index, the higher the diameter is, the higher the value becomes, which indicates that diameter growth can be related positively to CS; deducing a healthy crown development the higher this value becomes. The CSd values confirm this statement as the relationship is kept.

Keywords: biomass, morphometry, carbon, carbon dioxide, green weight, dry weight.

altura de la copa, diámetro de copa y altura total en 4 índices que describen una determinada estructura del árbol (cobertura copa (CC), índice de la Copa (CI), forma de copa (CS), sombra de copa (CSd)). Los resultados muestran, para los seis individuos evaluados, un valor relativamente alto para CC, el cual presenta el valor más bajo para el diámetro más pequeño; la cobertura de copa indica que la especie, en este grupo de edad, todavía está en crecimiento de manera exponencial y que su área fotosintética necesita todavía ser alta para sostener tal crecimiento. En cuanto al índice de forma de copa, entre mayor sea el diámetro, mayor es el valor que se obtiene, lo que indica que el crecimiento en diámetro puede estar relacionado positivamente a CS; deduciéndose un desarrollo sano de la copa entre mayor sea este valor. Los valores de CSd confirman esta afirmación al mantenerse la relación.

Palabras clave: biomasa, morfometría, carbono, dióxido de carbono, peso verde, peso seco

Introduction

Compared to natural forests, plantations have differences in the structure and composition of the canopy. Even for managed species in monocultures, a perceived difference is still present in the vertical structure. The characterization of the vertical structure can be an important element on plantations assessments, provided it can be demonstrated that variations in the tree architecture, besides the genetic constitution, obey to site conditions and/or management. The description of tree architecture through different parameters offers the possibility of characterizing trees and stands either for silvicultural management decision making (pruning, thinning and quality assessment of stems) or for research purposes (growth and yield) (Arias, 2005).

Volume calculations for all the possible logs obtained from a tree can be costly if performed repeatedly for every single stand, measuring the diameter and length of logs along the shaft. These measurements are likely taken by climbing, using optical instruments or simply cutting the tree down. To solve this problem, there are two alternatives: a) construction of volume tables for individual trees, or b) an adjustment stem analytical profile of trees (Ortiz, 2008). Morphometry of a tree and its variables are used to convey an idea of the inter-dimensional vertical space occupied by each tree, judging the degree of competition in the population and conclude about the stability, vitality and productivity of each individual (Durlo & Denardi, 1998).

Normally the different dimensions of an individual are statistically related one with another when looking at trees on a population level (Gould, 1966). This relation is consistent with the fact that the ontogenic development of individuals is the same for all trees with a history related variability; for instance, the proportions between height and diameter, between crown height and diameter, between biomass and diameter follow patterns that are equal for all trees, regardless of size, when growing under the same conditions (King, 1996; Archibald & Bond, 2003; Bohlman & O'Brien, 2006; Dietze et al., 2008). This is the basic principle of allometry, which is used to predict a dimension (typically volume or biomass) from a measurable variable (e.g. its diameter), being the allometric equation the formula that quantitatively formalizes such relationship.

Using allometric equations, based on mathematical relationships between relatively easily measurable parameters, such as diameter, allows the calculation of biomass of a given species in a non-destructive manner, which can be extrapolated to similar growth conditions (Montero & Montagnini, 2005).

The objectives of this study are to examine allometric equations for *Eucalyptus pellita* F.Muell under plantations and the use of crown architecture indexes to describe virility of the tree in relation to biomass and stand characteristics, and to evaluate their use on allometry description for plantation species.

Methodology

Characteristics of the study area

The study was conducted in a pure plantation and a provenance trial of *E.pellita*, owned by Agropical SA de CV, located in southeastern Mexico, specifically in the state of Tabasco, Huimanguillo municipality (Figure 1), at 17 ° 48 ‘31’’ N, 93 ° 40’ 26’’ W and 32 m in Tabasco, Mexico. The commercial plantation has an age of two and half years at the time of this study and an area of 24 ha. The Company desires to obtain reliable information on the production and behavior of *E.pellita* on forestry plantations; since the species has no plantation tradition in Mexico, and to respect all international protocols on introduction of exotic species, they have decided to establish a provenance trial. The area, where the species is planted, presents two types of climate: first, warm and humid with abundant rainfall in summer with thermal changes in the months of December and January, with and average temperature of 26.2 °C, having the maximum monthly average in May with 30.6 ° C, while the absolute maximum and minimum reach 45 ° C and 14 ° C, respectively Secondly a warm/humid climate with rainfall throughout the year in the south and southwest, these rainfall decreases slightly in winter time, rains in this period represent 14.4% of the annual total. The average temperature ranges between 25.4 ° C and 26.9 ° C. The rainfall regime is characterized by a yearly waterfall of 2290.3 mm in the month of September and zero in April.

The highest average wind speeds, are concentrated in the months of November and December with 30 km/h. winds (Hernández, et al. 2005). Soils are classified as acrisols, which are classified as acids, rich in organic matter and deficient in phosphorus and exchangeable bases, covering nearly all of them call Huimanguillo savanna (Hernández, et al. 2005).

Biomass assessment

Biomass calculations were performed as indicated by Schlegel, et al. (2000) on the Forest Biomass Sampling Procedures Manual, which describes the procedures and methodologies that are implemented on destructive testing of biomass sampling, usually quantified in tons per hectare of green or dry weight. Normally such sampling is performed by components, which correspond typically to mass of stem, branches, leaves, bark, leaves and dead wood. For the sampling conducted, six trees located in the plantation were selected from different diameter categories taking into account the growth variables. Biomass was only evaluated for the aerial section of each tree leaving the root biomass out of the study, due to logistic reasons.

According to Schlegel, et al. (2000) to conduct forest biomass sampling, the tree is divided into sections. Prior to felling the following information is recorded for each

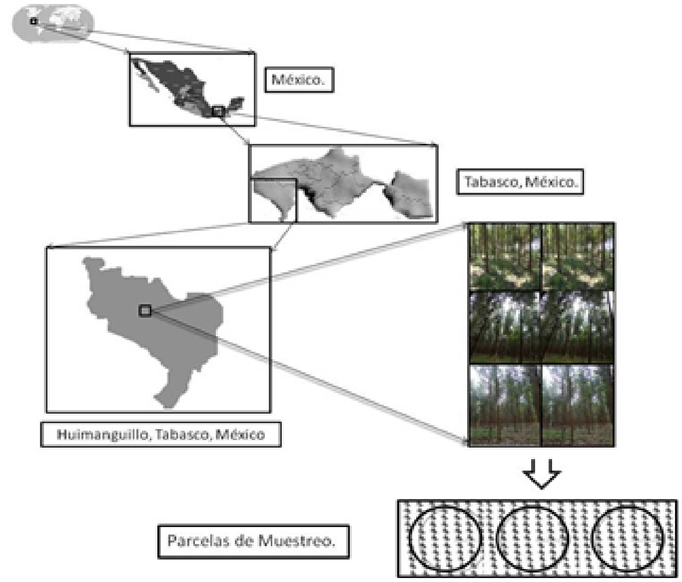

Figure 1. Physical location of the study area and the sampling area representation in the pure plantation of *Eucalyptus pellita* F.Muell, Tabasco, Mexico.

Figura 1. Ubicación física del área de estudio y la representación área de muestreo en la plantación de *Eucalyptus pellita* F.Muell , Tabasco , México.

of them: tree number, total height (m), dbh (cm), crown diameter (m). Tree felling was done as close as possible to the ground, measuring total height, height to crown start, diameter and height of stump, diameter with bark from the stump at every meter, varying slightly the measurement in the case of finding a stump branch; bark thickness along the main stem was also recorded at the sample point of diameter reading. Leaf and branch biomass was individually weighed. Subsequently, the stem section is weighted by separating it into 1 meter sections and obtaining individual measurement from each section. To determine diameter (dbh) and total height (h) ratio with respect to tree biomass components, linear regressions using the statistical program InfoStat® were performed. The models were selected by plotting the behavior of the model values against those previously recorded for biomass.

Crown variables assessment

Additional parameters for crown development were measured in order to obtain a correlation between dbh, volume and crown cover (Figure 2).

These variables will give an index of the “photosynthetic space” of each tree and it can be seen as a growth development variable for early and later stages.

$$\text{Crown Coverage:} \frac{\text{Crown Height (m)}}{\text{Total Height (m)}} * 100 \tag{1}$$

$$\text{Crown Index: } \frac{\text{Crown Height (m)}}{\text{Crown Diameter (m)}} \tag{2}$$

$$\text{Crown Shape: } \frac{\text{Crown Diameter (m)}}{\text{Crown Height (m)}} \tag{3}$$

$$\text{Crown Shade: } \frac{\text{Crown Diameter (m)}}{\text{Total Height (m)}} \tag{4}$$

To determine correlations between these variable and dbh and total height were analysis were performed using the statistical program InfoStat®. These indexes can shed light on the relationship between crown architecture and growth, considering the typical shape of *E.pellita* (Figure 3).

Statistical analysis of aboveground biomass

Statistically we used the higher value of the adjusted coefficient of determination (adjusted R^2) of each model (Parresol, 1999) considering statistical significance of parameters on each model, with probability of least $\alpha < 0.05$. After biomass estimation, the amount of carbon (C), carbon dioxide (CO_2) and volume equation for 30 months *E. pellita* plantation were estimated. Dry weight was determine by using the ratio of green weight /dry weight, obtained by García et al. (2004), at a research conducted biomass yield evaluation of *Eucalyptus pellita* in Pinar del Rio, Cuba, where stem ratio was 0.496 and 0.579 for foliage. Carbon was then calculated by multiplying dry weight multiplied by a factor of 0.5, and this result was further multiplied by 3.67 to obtain tons of CO_2

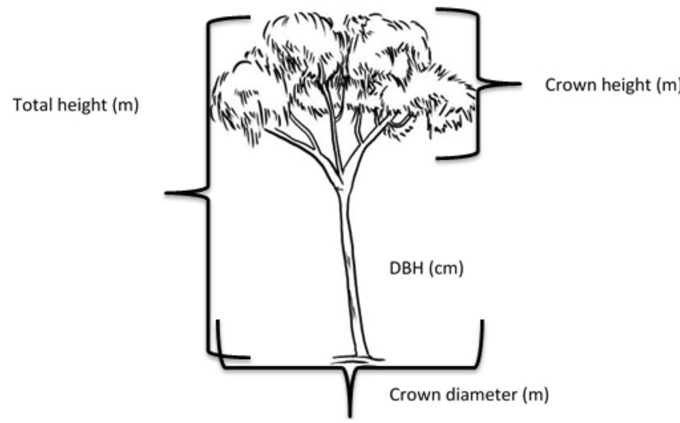

Figure 2. Crown variables used for relationships between dbh, volume and crown cover.

Figura 2. Variables copa utilizados para las relaciones entre diámeto a la altura del pecho, volumen y cobertura de copa.

Figure 3. *Eucalyptus pellita*, plantation at 30 month of age, at AGROPICAL S.A Company ranch C.V, Tabasco, México.

Figura 3. *Eucalipto pellita*, plantación de 30 meses de edad , en el rancho AGROPICAL SA Empresa CV , Tabasco , México.

Results and discussion

From the selected *Eucalyptus pellita* trees, a set of models for leaf, branch, stem and total biomass were calculated, these models are presented in Table 1.

The models were developed in a range of 12 to 18 cm of dbh and a total height range of 13 to 17 m; they are relatively simple models that use direct variables easily measured with small errors on dbh. The determination coefficients of these models are high, which is a satisfactory measure of the behavior of the model, where the R^2 is considered reasonable with values of 0.85 and up. The amount of trees to build the models can be considered small, based on a biomass and volume study for *Eucalyptus camaldulensis* conducted in a massive growth and yield project (Hughell, 1990) however the average age of that study is well within the range of the information here used. Leaf, stem and total biomass have high and similar correlation coefficients, being 0.93, 0.94 and 0.97 respectively; branch biomass has an R^2 of 0.85 where the additional height variable was used for its measurement indicating that the variable can be ambiguous to help predict branch biomass, however the value remains high.

In literature, not many studies are found on crown development related to site quality (Arias, 2005); therefore it is important to obtain this information in order to be able to link such crown indexes to the diagnose of the state of the plantation. Ebert & Rieger, 2000, presented a study for *Quercus rubor* L., where they show a strong

Table 1. Linear regression models to estimate biomass of different components from selected trees of *Eucalyptus pellita*, in the state of Tabasco, Mexico.

Tabla 1. Modelos de regresión lineal para estimar biomasa para diferentes componentes de árboles seleccionados de *Eucalyptus pellita,* en el estado de Tabasco, México.

Dependent Variable	Independent variable	Biomass Model (Ton)	R^2
Leaf Biomass	DBH	-0.028+0.03*DBH (cm)	0.93
Branch Biomass	DBH/h	-0.03+0.05*DBH (cm)/h (m)	0.85
Stem Biomass	DBH	-0.1+0.01*DBH (cm)	0.94
Total Biomass	DBH	-0.14+0.02*DBH (cm)	0.97

Where; DBH: Diameter at Breast height (cm), h:Height (m) p0.05 < p < 0.01= * (Significant), p< 0.01= ** (very significant)

Table 2. Crown variables from selected trees of *Eucalyptus pellita*, in the state of Tabasco, Mexico.

Tabla 2. Variables de copa para árboles seleccionados de *Eucalyptus pellita*, en el estado de Tabasco, México.

Tree N°	DBH(cm)	Crown Diameter (m)	Total Height (m)	Crown Height(m)	Crown shape	Crown Shade	Crown index	Crown coverage (%)
1	13.4	2.9	14.55	7.7	0.38	0.20	2.66	52.92
2	12.5	3.25	14.82	7.8	0.42	0.22	2.40	52.63
3	14.5	3.95	15.9	6.2	0.64	0.25	1.57	38.99
4	17	3.65	16.55	5.95	0.61	0.22	1.63	35.95
5	11.5	2.78	13.83	4.75	0.59	0.20	1.71	34.35
6	17.6	3.8	16.49	6.9	0.55	0.23	1.82	41.84

correlation was found between DBH and volume with crown projection area, crown length and crown diameter. The radiation received by the tree crown varies with space and time like many other physical aspects of the tree. Its spatial variation is determined by the crown structure and by the incident radiation which fluctuates during the day and therefore induces temporal change in the radiation regime within the tree crown (Wang & Jarvis, 1990). The present study relates crown height, crown diameter and total height into 4 indexes which describe a given structure of the tree (Crown Coverage (CC), Crown Index (CI), Crown Shape (CS)) as well as their state in the plantation in terms of structure and even competition for space (Crown Shade (CSd)). These indexes, seen in Table 2, help provide an idea of the strength of the crown, and tits photosynthetic area distribution, which can obey to site and local meteorological (radiation incidence) conditions.

The results show, for the six sampled individuals, a relatively high value for CC, showing the lowest value for the smallest diameter; since the higher this % is, more crown on tree there would be, we need to consider other aspects such as height, age of plantation and phenology of the species. Crown coverage indicates that the species at this age class is still growing rather exponentially and that its photosynthetic area needs still to be high to sustain such growth. Crown index is a parameter that is subjected to the structure of the crown; more crown height allows the tree to take advantage of lateral light incidence. Eucalyptus species in general possess a large crown height and narrow crown diameter which enables them to use efficiently early and late incidence of radiation; if we have a CI of low value this indicates a different structure on which the tree might be dependent on more direct light from above. Concerning crown shape the higher the diameter is, the higher the value becomes, which indicates that diameter growth can be related positively to CS; as the higher this value is we can deduce a healthy crown development. The CSd values help sustain this statement as we see that the relationship is kept. Crown biomass and shape are of importance not only due to the vital function of radiation interception and consequent growth; recently in the last couple of decades the necessity of accounting for the biomass from that section of the tree has become of importance to calibrate biomass expansion factors (Kuyah, et al. 2015). The structure of tree crowns are likely to vary with time of year and age of stand, as do the physical and physiological properties of the leaves within the tree crown, it is therefore imperative to consider results here restricted to the early age of the plantation.

The amount of information here presented to calculate the indexes does not lead to definite conclusions, but allows understanding the dynamics of the crown at a young age, since the amount of biomass, as reflected by coverage indicates that in order for the species to sustain such a rapid growth it must have a large enough crown to accomplish its required photosynthetic activity. Several studies have been made on the influence of crown shape

Table 3. Correlation of crown variables from selected trees of *Eucalyptus pellita*, in the state of Tabasco, Mexico.

Tabla 3. Correlación de las variables de copa para árboles seleccionados de *Eucalyptus pellita*, en el estado de Tabasco, México.

Variable 1	Variable 2	n	Pearson (correlation index)	p
DBH (cm)	Crown shape	6	0.38	0.4577
DBH (cm)	Crown Shade	6	0.51	0.3046
Total Height (m)	Crown shape	6	0.47	0.3523
Total Height (m)	Crown Shade	6	0.72	0.1102

Table 4. Amount of carbon and carbon dioxide stored in six *Eucalyptus pellita* trees, at 30 months of age in the state of Tabasco, Mexico.

Tabla 4. Cantidad de carbón y dióxido de carbono almacenado en seis árboles de *Eucalyptus pellita*, a los 30 meses de edad en el estado de Tabasco, Mexico.

Sample tree	DBH (cm)	Stem (kg)	Foliage (kg)	R		C		CO_2	
1	13.40	99.72	32.52	49.46	18.83	24.73	9.41	90.76	34.55
2	12.50	72.48	25.07	35.95	14.52	17.98	7.26	65.97	26.64
3	14.50	115.35	38.97	57.22	22.56	28.61	11.28	104.99	41.41
4	17.00	158.28	46.43	78.51	26.88	39.25	13.44	144.06	49.33
5	11.50	65.75	19.62	32.61	11.36	16.31	5.68	59.84	20.84
6	17.60	142.58	53.79	70.72	31.14	35.36	15.57	129.77	57.15
Average	14.42	109.03	36.07	54.08	20.88	27.04	10.44	99.23	38.32

R = green weight / weight (stem (0.496), foliage (0.579)), C = Carbon, CO_2 = Carbon Dioxide.

on PAR absorption, in which there is an indication on the effect of crown shape on the photosynthetic rate of a tree; however the simulations studies have indicated that the total area of leaves and their spatial distribution within the crown are far more important than either crown shape or leaf inclination (Wang & Jarvis, 1990).

Table 3 examines the correlation of CS and CSd with DBH and total height; as defined, crown shade is the reason between the crown diameter and total height, the correlation values are therefore higher with height than with dbh. From crown biomass it is possible to calculate the amount of carbon present at a given time and the change in the amount of biomass accumulated trough time functioning as a carbon sink; along with other easily measured variables this will give the sink in total. Information on crown structure and morphology are indicators of vitality, providing scientists and foresters with a generic tool to study large-scale forest response to various stresses; the reduction of crown area can serve as a diagnosis tool to give insight simultaneously to growth reduction and probability of death among various tropical tree species (Rutishauser, et al. 2011). The R^2 obtained here however show a very low predictability, indicating that more individuals are needed to approximate any correlations between these variables.

Many studies have examined the characteristics of crown form by allometric relationships among dimensions. Architecture of tree form is determined mainly by growth in each dimension. In forests, species with wider crowns and thicker trunk increase assimilative capacity and the probability of survival under canopy, while those with narrower crown and thinner trunk can grow faster in gaps due to lower biomass increment required per unit height growth (Takahashi, 1996). Under plantations conditions, all trees have the same growth space and would react in height growth at the start of establishment. Density plays an important role on growth of the stand; but crown shape might be more affected by immediate neighbor competition; therefore, studies on the architecture of crown forms should take account of the heterogeneity in local environments. There are a few studies on the response of growth rate and assimilate partitioning to local light environments (King, 1991, 1994). There is, however, no study that addresses the response of a whole architecture to different environments. Immediate neighbors, rather than average density, have been appreciated to affect the survival and the growth of a target plant (Takahashi, 1996); from this we can infer that adaptation on crown architecture is an important feature to optimize growth. The indexes here presented are a start point to mathematically understand relations, but species stand growth characteristics are also to be noted. Many eucalyptus species grown on single species stand, such as the condition that a plantation provides, therefore the CS, CC and CI are a reflection on crown architecture.

As see in Table 4, carbon content was obtained by multiplying dry mass by the IPCC carbon factor (IPCC, 2006), normally taken as 0.5, and the CO_2 is obtained by multiplying carbon by the equivalent amount of carbon dioxide which is stored when capturing a ton of carbon, which is the same as using the molecular weight rate factor or 44/12 (3.67). In average the carbon stored per tree in the stem was 27.04 kg and 10.44 kg in the foliage; average carbon dioxide storage in the stem was 99.23 kg of CO_2 and 38.32 kg CO_2 in the foliage. Foliage included the branch mass as branches were no higher than 4 cm in diameter, and logistically difficult to separate thus they were summed up as part of the component. From the six selected trees for the study the highest fresh weight in the stem was 158 kilograms (kg) and the lowest 66 kg, and the highest leaf fresh weight was 53.8 kg with its lowest at 19.62 kg; making the values almost coincide with the highest mass for the stem.

Plantation density is at 963 trees per hectare; giving a reservoir of 36.08 tons of carbon per hectare and 132.45 tons of carbon dioxide, at a plantation just 30 months after establishment. The time frame for these data is still very short, nevertheless the apparent fast growth gives a growth rate of rate of 14.43 tons of C/ha and 52.98 Tons of CO_2. Considering that the species has been recently introduced, such results on rates of accumulation indicate than *Eucalyptus pellita* is commercially an optimal species for reforestation and clean development mechanism (CDM) projects.

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