Above-ground carbon absorption in young *Eucalyptus globulus* plantations in Uruguay

Absorção aérea de carbono em plantações jovens de *Eucalyptus globulus* no Uruguai

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**Resumo**

Carbon absorption in young *Eucalyptus globulus* Labill plantations was quantified in four sites in the western region of Uruguay: Algorta, Bequeló, Quebracho and Tres Bocas. Plantation densities varied from 733 to 1300 trees ha⁻¹, and ages ranged from three to nine years. We selected 132 trees from twenty 300 m² circular plots. Each tree was divided into four components: tree bole, live branches, dead branches, and leaves, and carbon content was determined for each component. Total above-ground carbon content was calculated by adding the carbon content of the four components. We evaluated 20 allometric function types to predict carbon absorption: one function per site, eight global functions for all sites combined, and eight global functions including a dummy variable to implicitly identify sites. For all components, carbon absorption functions that included diameter at breast height (dbh) and tree height as explanatory variables provided the smallest standard error of estimate (SEE) on all sites. The mean SEE of all sites was 3.89 Kg C for total above-ground carbon absorption, and 3.84, 1.06, 1.26, and 0.59 Kg C for tree bole, leaves, live branches and dead branches respectively. An ANOVA test indicated significant differences in the mean annual increment (MAI) of carbon absorption among the four sites, with Bequeló and Tres Bocas having the largest carbon absorption rates followed by Quebracho and Algorta. The ANOVA test included plantation density as a covariate, which was significant only for the tree bole and total above-ground.

**Keywords**: Biomass, allometric functions, dummy variable

**Abstract**

O objetivo do presente trabalho foi quantificar a absorção de carbono em plantações de *Eucalyptus globulus* em quatro zonas localizadas no litoral oeste da República Oriental do Uruguai (Algorta, Bequeló, Quebracho e Tres Bocas), as densidades de plantação variavam de 733 a 1.300 árvores ha⁻¹ e as idades entre 3 e 9 anos. Para quantificar o carbono absorvido foram escolhidas 132 árvores, provenientes de 20 parcelas circulares de 300 m². As árvores foram divididas em quatro frações: fuste, folhas, galhos verdes e galhos secos; a quinta fração corresponde ao total aéreo, resultado da adição das frações. Para cada componente por zona foi escolhida uma função que apresentou o menor erro padrão de estimativa, para o qual a seleção foi feita entre 20 funções alométricas (4 por zona, 8 para o conjunto das zonas e 8 para o conjunto das zonas com variáveis Dummy). Para todas as frações foi escolhida uma função por zona, que em sua grande maioria incorporava como variável explicativa DAP e a altura das árvores. O erro padrão médio por zona foi de 3.89, 3.84, 1.06, 1.26 y 0.59 Kg C para a fração total aéreo, fuste, folhas, galhos verdes e galhos secos, respectivamente. Mediante análise de variância identificou-se diferenças significativas do incremento médio anual da absorção de carbono. As zonas de maior absorção de carbono encontradas foram Bequeló e Tres Bocas, seguidas da zona de Quebracho e Algorta. A análise de variância incorporou a densidade de plantação como covariável, resultando ser altamente significativa para a fração total aéreo e fuste, porém não significativa para as demais frações.

**Palavras-chave**: Biomassa, funções alométrica, variáveis dummy.

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INTRODUCTION

Forest plantations are considered an important mitigating factor against the predicted increase in atmospheric carbon concentration because tree species can efficiently absorb carbon (HUNTER, 2001; KURZ et al., 2009; SANDS et al., 1999). In Uruguay, the most abundantly planted tree species is Eucalyptus globulus Labill, which covers more than 272,000 ha in plantations (MGAP, 2012). This forest resource has been quantified in terms of timber volume (MORAS, 2010) and biomass production (VALERO et al., 2006); however, no studies have estimated the carbon absorption potential of these forest plantations. Literature suggests that forest plantations can provide larger carbon absorption rates than natural forests. For example, 30-year Pinus taeda L. plantations in the United States presented a carbon storage that is on average 87% larger than that of comparable natural forests (EAV et al., 2000). Tree biomass and thus carbon storage can be increased by selecting desirable seed provenance (GRANEY, 1979; POPE; RETZLAFF et al., 2001); by implementing opportune thinning treatments (HORNER et al., 2010; LOZA-BALBUENA, 2001; MUNOZ et al., 2008); by applying fertilization and weed control treatments (JOKELA; MARTIN, 2000; STAPE et al., 2006) and by increasing rotation age (LISKI et al., 2001). Plantation density can also have a large effect on carbon storage. While increasing tree density can increase carbon storage, raising densities too high can reduce net absorption due to an increase of suppressed trees (NAIDU, et al., 1998). Other studies including Horner et al. (2010), and Pérez-Cruzado et al. (2011) and Vallejos et al. (2002), also found lower carbon storage rates associated with larger plantation densities. Furthermore, Carrasco-Letelier et al. (2004), Horner et al. (2010) and Specht and West (2003), reported that forest plantations cannot always be considered carbon sinks because some Eucalyptus species might reduce organic carbon content in the soil.

Destructive sampling is frequently used to determine tree biomass (EBUY et al., 2011; PÉREZ-CRUZADO; RODRÍGUEZ-SOALLEIRO, 2011). Gibbs et al. (2007) summarize the sampling procedure in the following steps: i) determining the green biomass for each component of sampled trees, ii) obtaining a sample from each tree component (i.e., bole, leaves, live and dead branches) and measuring both green and dry biomass in the sample, and iii) applying proportions to obtain dry biomass for each component (Dry biomass = Green biomass × Dry biomass/sample/ Green biomasssample). The amount of carbon stored by each tree component can then be determined by multiplying its biomass and a specific carbon fraction, defined as the carbon content per unit biomass. Traditionally, 0.5 has been used as the carbon fraction for this calculation (GIBBS et al., 2007; SOMOGYI et al., 2007). However, some studies have reported smaller values for total above-ground carbon in Eucalyptus globulus (GAYOSO et al., 2002; SCHUMACHER; WITSCHORECH, 2004) and larger values for their leaves (BRAÑAS et al., 2000). Similar values have been reported for Eucalyptus cladocalyx F. Muell. (PAUL et al., 2008). In the case of Pinus pinea L. Correia et al. (2010) reported a carbon fraction value lower than 0.5 for needles and values larger than 0.5 for all other components. Lastly, Oliver et al. (2011) reported values larger than 0.5 for all components in Pinus radiata (D. Don) stands in New Zealand.

The most utilized allometric function to estimate tree biomass is biomass = bo dbhb1. The most utilized allometric function to estimate tree biomass is biomass = bo dbhb1 (SPECHT; WEST, 2003; SOMOGYI et al., 2007; ZIANIS et al., 2011). To improve prediction quality, it has been suggested to include tree height (h), biomass = bo dbhb1 h b2. However, the predictive power improvement has been marginal (MONTAGU et al., 2005; PÉREZ-CRUZADO; RODRÍGUEZ-SOALLEIRO, 2011; VERWIJST; TELENIUS, 1999). For example, Paul et al. (2008) found that including tree height with dbh in biomass improved the efficiency of prediction by no more than 6%. These functions should be used in their nonlinear form to conserve the additive nature of the residuals. However, in many studies logarithmic transformations are applied to use the least squares method. Although mathematically both types of functions are equivalent, the transformation introduces bias to the estimations (MONTAGU et al., 2005; PAUL et al., 2008; PARRESOL, 1999; SPECHT; WEST, 2003; ZIANIS; MENCUCCINI, 2004).

Most functions used to predict tree biomass or carbon absorption are developed for each tree component with and without separation by geographic regions (sites). Dummy variables are also used to implicitly identify sites in a single function, thus increasing the degrees of freedom to estimate population parameters and improving the relative precision of the estimates (GUJARATI, 1996). There are only a few studies incorpo-
rating dummy variables in allometric functions. For example, Verwijst and Telenius (1999) used dummy variables to identify the location of shoots in short rotation bioenergy plantations, but predictive quality was lower than a generalized function without dummy variables.

The objective of this study was to select allometric functions to estimate the carbon absorption by each component (bole, live branches, dead branches, and leaves) as well as total above-ground of young Eucalyptus globulus Labill trees growing in western Uruguay. Four types of allometric functions were evaluated: i) two functions by site: one considering only the dbh, and another one considering dbh and tree height as explanatory variables; and ii) two global functions: one combining all four sites and another one using dummy variables to identify site locations. An ANOVA test was applied to identify differences in mean annual increment (MAI) of carbon absorption among the four sites.

**METHODOLOGY**

Measurements were made in young unmanaged Eucalyptus globulus Labill. plantations belonging to the EUFORES forest company in Uruguay. These plantations are located in the sedimentary basin in the western part of the country. Topography consists mostly of mid-elevation plains with low to moderate slopes and elevation lower than 100 m a. s. l. (BOSSI et al., 1998). Mean lowest and highest temperatures are 10.5 °C and 22.5 °C occurring during the months of June and January respectively, and mean annual precipitation is 1,174 mm (CRUZ et al., 2000).

We used simple random sampling to place twenty 300 m² circular sampling plots within the four sites: 6 plots in the Algorta site, 6 plots in the Bequeló site, 6 plots in the Quebracho site, and 2 plots in the Tres Bocas site. Plantation ages in these four sites varied from 3 to 9 years, and density ranged from 733 to 1,300 trees ha⁻¹. Plot locations were representative of the average tree growth in each site based on permanent plot data provided by the EUFORES forest company. Inside each plot, dbh was measured for all trees using a millimeter-precision caliper. A total of 617 trees were measured in all 20 plots. In each plot, 6 or 7 trees representative of the diameter class were felled. A total of 40 trees were felled in Algorta, 42 in Bequeló, 36 in Quebracho, and 14 in Tres Bocas. A millimeter-precision distance tape was used to measure the length of felled trees, which was assumed to be the tree height. Branches were separated from the bole using an axe or loppers based on their diameter, and leaves were manually separated from the branches. The mass of the bole was obtained by bucking the bole into 2-meter sections and adding their masses. The green mass of all components was determined using a Thunderbird field scale with a precision of 200 g.

From each component, a sample was extracted and sent to a laboratory where green mass was measured using a 1 gram-precission electronic My Weigh KD-600 scale. Then the samples were dried in a Venticell at 65 °C until constant weight was achieved, which was considered as the dry mass of the sample. The dry mass of each component was determined by multiplying the green mass measured in the field and the proportion between dry and green mass measured in the laboratory. The carbon content by component was then obtained by multiplying the component’s dry mass and the corresponding carbon fraction. We used carbon fraction values of 0.42, 0.46, 0.40, and 0.40 for the bole, leaves, live branches, and dead branches respectively as reported by Schumacher and Witschrech (2004). These values were selected due to the proximity and similarity of tree ages observed in Schumacher and Witschrech (2004). Lastly, the total above-ground carbon content for a given tree was determined by adding the carbon content of all four tree components.

All statistical analyses were conducted using Statgraphics Centurion XVI (StatPoint Technologies, Warrenton-Virginia, USA). For each component, we evaluated two nonlinear functions to predict carbon absorption; one based on dbh alone and another based on dbh and tree height (Eqs. 1 and 2).

\[
C = b_0 \text{dbh}^{h_i} \quad (1)
\]

\[
C = b_0 \text{dbh}^{h_i} \text{h} \quad (2)
\]

where C is the amount of carbon absorption by the component (kg); dbh is the diameter at breast height of the tree (cm); h is the tree height (m); bo is the regression constant, and bi are the regression coefficients (i = 1 and 2). We used the Marquardt algorithm (MARQUARDT, 1963) to fit these nonlinear functions by component in each site.

These functions were linearized by applying a logarithmic transformation (eqs. 3 and 4) and applied the least squares method to fit the linear functions by component and site.
The selected functions were used to estimate the carbon absorption for each component in each site. A parametric ANOVA test was then used to determine if there were significant differences in carbon absorption rates between sites. We analyzed the MAI of carbon absorption (Mg ha\(^{-1}\)year\(^{-1}\)) with tree density as a covariate. Residuals were tested for normality and homoscedasticity using the W statistic of the Shapiro-Wilk test (SHAPIRO; WILK, 1965) and the Z statistic of the Levene test (LEVENE, 1960) respectively.

**RESULTS AND DISCUSSION**

We characterized the growth in each site based on the MAI of dbh and tree height due to differences in plantation density and age (Table 1). Plots in the Bequeló site with trees between 3 and 5 years old presented the highest MAIs of dbh (≥ 3.4 cm/year) and height (≥ 3.0 m/year). These growth rates corresponded with the lowest tree densities (≤ 1,033 trees/ha), which could evidence the favorable effect of a reduced competition. Independent of site and tree density, the lowest growth rates were associated with the oldest trees, 8 and 9 years, that had MAIs of dbh and height less than 1.8 cm year\(^{-1}\) and 2.1 m year\(^{-1}\) respectively.

The carbon content in the 132 felled trees varied with plantation age and site (Table 2), but as expected, these differences seem to correspond to variations in the MAI of dbh and height as well as plantation density (Table 1). For example, 4-year old trees in the Bequeló site indicated a MAI of carbon absorption 38% larger than 4-year old trees in the Algorta site, which is likely explained by the Bequeló site’s 17% larger MAI of dbh and 30% lower plantation density. Similarly, 8-year old trees in the Quebracho site exhibit a MAI of carbon absorption about 9% larger than 8-year old trees in the Algorta site, which corresponds to larger MAI of dbh and height. In general, the highest carbon absorption rates are associated with the highest plantation age and lowest plantation density; the Bequeló site has the highest carbon absorption MAI followed by Tres Bocas, Quebracho and Algorta sites. The exception are plots located in 5-year old plantations in Bequeló site that present relatively larger carbon absorption rates due to the greater amount of carbon content in the tree bole, leaves, and live branches that likely resulted from lower plantation density.
Tabela 1. Sampling information obtained from plots located in the four sites considered in the study.
Table 1. Informação obtida das parcelas de amostragem nas quatro zonas consideradas na pesquisa.

<table>
<thead>
<tr>
<th>Site</th>
<th>Age (years)</th>
<th>MAI dbh (cm year(^{-1}))</th>
<th>MAI H (m year(^{-1}))</th>
<th>N (tres ha(^{-1}))</th>
<th>Number of plots</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algorta</td>
<td>4</td>
<td>2.9</td>
<td>3.1</td>
<td>1,300</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>2.4</td>
<td>2.5</td>
<td>1,033</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>1.7</td>
<td>1.9</td>
<td>1,033</td>
<td>3</td>
</tr>
<tr>
<td>Bequeló</td>
<td>3</td>
<td>4.4</td>
<td>3.8</td>
<td>833</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>3.4</td>
<td>3.3</td>
<td>1,033</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>3.4</td>
<td>3.0</td>
<td>733</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>2.5</td>
<td>2.7</td>
<td>1,233</td>
<td>2</td>
</tr>
<tr>
<td>Quebracho</td>
<td>8</td>
<td>1.8</td>
<td>2.1</td>
<td>956</td>
<td>6</td>
</tr>
<tr>
<td>Tres Bocas</td>
<td>9</td>
<td>1.8</td>
<td>2.0</td>
<td>1,133</td>
<td>2</td>
</tr>
</tbody>
</table>

On average, carbon absorption allocated to the tree bole, leaves, live branches, and dead branches was 78%, 10%, 9%, and 4% of the total above-ground carbon absorption respectively. The proportion of autotrophic tissue (leaves) to heterotrophic tissue (bole plus branches) was larger for the youngest trees compared with older trees. For example, carbon content in leaves was about 15% of the total above-ground carbon for 3-year old trees and about 7% for 8- and 9-year old trees. Carbon allocated to the bole also ranged from 69% for the smallest trees to 85% for the oldest trees. Similar results have been found in other tree species including *Pinus taeda* in North Carolina, US (NAIDU et al., 1998), and *Abies nephrolepis* in Northeast China (WANG et al., 2011).

During the cluster analysis, we identified two clusters to fit global functions to predict carbon absorption by the tree bole and total-above-ground. The first cluster consisted solely of the Algorta site, while the second cluster was formed by the remaining three sites. In addition, two clusters were identified for the leaves, live branches, and dead branches. The composition of the clusters for these three components was identical: the first cluster consisted of the Algorta and Bequeló sites, and the second cluster was formed by the Quebracho and Tres Bocas sites.

The results from fitting all functions and calculating the associated 400 SEE values indicated that applying cluster analysis to the global functions improved predictive quality by providing smaller SEE values than most global functions without clusters (Figure 1). On average for all sites and components, clustering slightly reduced the SEE values associated with global functions from 3.36 Kg. to 3.32 Kg. The impact of clustering was more noticeable for global functions with dummy variables where average SEE values were reduced from 3.07 Kg. to 2.90 Kg. Global functions including dummy variables provided better results for total above-ground, tree bole, and live branches but slightly worse for dead branches and leaves. Lastly, site functions [eqs. 1-4] provided the best fit with the smallest SEE values for all tree components and sites with SEE average of 2.71 Kg. Among the site functions, non-linear functions [eqs. 1-2] were consistently better and log-transformed functions [eqs. 3-4] independent of tree component and site (Figure 1).

Sixty percent of all the selected non-linear functions included both dbh and height [eq. 2] as predictor variables (Table 3). The inclusion of tree height in these functions improved SEE by 3% to 39%. As expected, this function yielded the lowest error in estimating tree bole...
carbon absorption in all four sites. With the exception of the Bequeló site, tree height did not improve estimation of carbon absorption by leaves. However, tree height was also significant in predicting carbon absorption by live and dead branches in the Bequeló and Quebracho sites. The selected carbon absorption functions of tree boles provided the best goodness-of-fit measures with adjusted R² ranging from 95% to 98% and SEE values between 3.2 and 4.4 kg depending on site. Carbon absorption functions for leaves, live branches, and dead branches presented adjusted R² values of 78%, 73%, and 45% respectively. The higher goodness-of-fit measures of carbon absorption functions for the tree bole might be explained because both dbh and tree height are highly correlated with bole volume and thus biomass. Including crown dimensions such as crown width, depth, and/or crown ratio as variables would likely improve the efficiency of carbon absorption functions for leaves and branches. In general, carbon absorption functions for the total above-ground present similar predictive quality to those for the tree bole because the tree bole contributes a large portion of total above-ground carbon absorption.
We used the selected functions to quantify the amount of carbon absorption in the 20 sample plots. The MAI of total above-ground carbon absorption rates ranged from 4.73 to 6.68 Mg ha\(^{-1}\) year\(^{-1}\) based on tree component and site (Figure 2). These results are higher than the ones published by Brañas et al. (2000), but lower than those published by Miehle et al. (2006).

**Figure 2.** Duncan’s multiple range test of the MAI carbon absorption (Mg ha\(^{-1}\) year\(^{-1}\) of C) a) total above-ground, b) Bole, c) Leaves, d) Live Branches and e) Dead Branches.
and Pérez-Cruzado et al. (2011) with values of 4.2, 8.5 and 7.1 Mg ha⁻¹ year⁻¹ respectively for the same species.

As expected, plantation age influenced the amount of total above-ground carbon absorption. Plots located in older plantations exhibited larger carbon content. Plantation density also has an effect on the amount of carbon absorption. For plantations of the same age, lower densities seem to correspond to slightly higher carbon absorption rates. Tree bole carbon absorption as a proportion of total above-ground carbon absorption increases with age. For example, in the Bequeló site this proportion ranged from 66% in plots located in 3-year old plantations to 84% in plots with 6-year old trees. Similarly, tree bole carbon absorption, as a proportion of total above-ground carbon absorption, decreases in plots located on sites with lower plantation density. On the other hand, carbon absorption by leaves and branches, as a proportion of total above-ground carbon absorption, increases with decreasing plantation density. This is likely because trees in low density plots do not have to allocate as much growth/biomass into the bole, in order to avoid light interception by neighboring trees.

Comparisons of carbon absorption rates among all four sites, conducted through a parametric ANOVA test, show significant differences for all tree components as well as the total above-ground (Figure 2). The validity of the ANOVA test was confirmed as evidenced by the non-significant W statistic of the Shapiro-Wilk test and the Z statistic of the Levene test, which indicated normally distributed and homoscedastic residuals for all tree components. Plantation density, used as a covariate in the ANOVA test, was highly significant ($\rho \leq 0.01$) for the tree bole and total above-ground carbon absorption but not for the remaining tree components.

Additionally, a Duncan’s multiple ranges test (DUNCAN, 1955) compared average carbon absorption rates among sites for each tree component and total above-ground carbon absorption (Figure 2). Results indicate that the Bequeló and Tres Bocas sites have the largest MAI of total above-ground carbon absorption, 6.7 and 6.3 Mg ha⁻¹ year⁻¹ respectively, followed by the Quebracho and Algorta sites, 4.7 and 4.9 Mg ha⁻¹ year⁻¹ respectively. There were no significant differences between the Bequeló and Tres Bocas, but both were significantly different from the other two sites when comparing total above-ground carbon absorption and carbon absorption by the tree bole. Differences among sites in carbon absorption from leaves and branches were less evident. Lastly, the separation of the Bequeló and Tres Bocas sites from the Algorta and Quebracho sites based on carbon absorption rates was also confirmed by the cluster analysis conducted for the global functions with dummy variables.

**CONCLUSIONS**

Predictive functions separated by site for each component provided the best goodness-of-fit measures. Functions to predict total above-ground carbon absorption presented adjusted $R^2$ values varying from 0.95 to 0.98 and standard error of estimate ranging from 4% to7%. Predictive quality of carbon absorption functions for the tree bole presented similar results as those to predict total above-ground carbon absorption. Functions associated to the remaining tree components, leaves and branches, present lower predictive quality with adjusted $R^2$ and standard error of estimates values ranging from 0.25 to 0.87 and 13 to 25%, respectively. All selected functions included dbh as a predictive variable and 60% included both dbh and tree height.

Plantation density had an effect on MAI of total above-ground carbon absorption as well as carbon absorbed by tree bole because only young plantations were considered. Carbon absorption by leaves, live branches, and dead branches was not influenced by the number of trees per ha. The MAI of carbon absorption presented statistically significant differences among the four different sites. The Bequeló and Tres Bocas sites presented the largest carbon absorption rates followed by the Quebracho and Algorta sites.

The use of these functions selected in our study offers the potential to expand management alternatives to decision-makers. With the ability to quantify carbon absorption, it may be possible to implement Clean Development Mechanism Projects, as defined in the Kyoto Protocol (IPCC, 2007), with *Eucalyptus globulus* plantations in western Uruguay.

**REFERENCES**


