SCIENTIA
FORESTALIS

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

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

Oscar Vallejos-Barra[1], Gustavo Daniluk-Mosquera[2], Guillermo Moras[3], Mauricio Ponce-Donoso[4], Marco A. Contreras[5]

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 quarto 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 a função que apresentou o menor erro padrão de estimative, 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 Dummies). Para todas as frações foi escolhida uma função por zona, que em sua grande maioria incorporava como variável explicativa o 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, folias, 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 carbon 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.

[1]Assistant Professor of Forest Mensuration, Forest Production Department, College of Forest Sciences, University of Talca, 2 Norte 685, Talca, Chile, E-mail: ovallejo@utalca.cl.

[2]Professor of Harvesting and Forest Certification, Director of the Forest Production and Wood Technology Department, College of Agronomy, University of the Republic. Avenida Garzón 780, Montevideo, Uruguay, E-mail: gdaniluk@fagro.edu.uy

[3]Assistant Professor of Forest Mensuration, Forest Production and Wood Technology Department, College of Agronomy, University of the Republic. Avenida Garzón 780, Montevideo, Uruguay, Email: gmoras@fagro.edu.uy

[4]Assistant Professor of Forest Economy, Environmental and Forest Management Department, College of Forest Sciences, University of Talca 2. Norte 685, Talca, Chile, E-mail: mponce@utalca.cl

[5]Assistant Professor of Forest Management, Department of Forestry, College of Agriculture , University of Kentucky. 214 Thomas Poe Cooper Building (Office 204), Lexington, KY 40546-0073, USA, E-mail: marco.contreras@uky.edu

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; MUÑOZ 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 (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 dbhb1hb2. 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 incorporating 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-precision 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).

$$C = b_0\, dbh^{b_1} \qquad (1)$$

$$C = b_0\, dbh^{b_1} h^{b_2} \qquad (2)$$

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.

$$\mathrm{Log(C)} = b_0 + b_1 \mathrm{Log(dbh)} \quad (3)$$

$$\mathrm{Log(C)} = b_0 + b_1 \mathrm{Log(dbh)} + b_1 \mathrm{Log(dbh)} \quad (4)$$

We also evaluated these four functions globally for each component by combining carbon content data from all four sites. Lastly, dummy variables were added to these global functions to implicitly identify the different sites (Eqs. 5 – 8).

$$C = (b_0 z_1 + b_1 z_2 + b_2 z_3 + b_3 z_4)\ \mathrm{dbh}^{b_4} \quad (5)$$

$$C = (b_0 z_1 + b_1 z_2 + b_2 z_3 + b_3 z_4) \mathrm{dbh}^{b_4} h^{b_5} \quad (6)$$

$$C = b_0\ \mathrm{dbh}^{(b_4 z_1 + b_5 z_2 + b_6 z_3 + b_7 z_4)} \quad (7)$$

$$C = b_0\ \mathrm{dbh}^{(b_4 z_1 + b_5 z_2 + b_6 z_3 + b_7 z_4)} h^{(b_8 z_1 + b_9 z_2 + b_{10} z_3 + b_{11} z_4)} \quad (8)$$

where bj (j =0, 1,…,3) are the regression constants, bk (k = 4, 5, … , 11) are the regression coefficients, and zm(m = 1, 2,… 4) are binary variables indicating each site (zm = 1 if it indicates the site, and 0 otherwise).

Through a cluster analysis (EVERITT et al., 2011), we defined sites with similar characteristics. Clusters were identified using the Ward's method and the Euclidian distances. For each tree component, carbon absorption data were then combined based on the sites forming the identified clusters to fit the global functions, with and without dummy variables (eqs. 5 – 8). The cluster analysis provided additional information to evaluate the need to separate growth and carbon content information by site.

We fitted carbon content data to develop 184 functions: 80 site functions, 40 global functions, and 64 global functions applied to the clusters. Firstly, the 80 site functions resulted from: 4 site functions [eqs. 1-4] × 4 sites × (4 components + total above-ground). Secondly, the 40 global functions came from: 4 global functions [eqs. 1-4] × (4 components + total above-ground) + 4 global functions with dummy variables [eqs. 5-8] × (4 components + total above-ground)). Lastly, the 64 global functions applied to clusters resulted from: 4 global functions × 8 clusters + 4 global functions with dummy variables × 8 clusters.

A total of 400 standard errors of estimation (SEE) values were calculated to evaluate the predictive quality of carbon absorption functions for each tree component, site, and function type(((4 components + total above-ground)×4 sites)×(4 site function + 4 global functions + 4 global functions with dummy variables + 4 global functions applied to clusters + 4 global functions with dummy variables by cluster)). Finally, the function with the lowest SEE value was selected for each 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 $treesha^{-1}$), 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.

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

Tabela 2. Measured average MAI of carbon absorption per tree by site and tree component.
Table 2. Incremento médio anual (IMA) do carbono absorvido pelas árvores segundo zona, idade e fração.

Site	Age (years)	MAI Carbon (kg)				
		Total above-ground	Bole	Leaves	Live Branches	Dead Branches
Algorta	4	4.42	3.22	0.48	0.41	0.30
	5	5.53	4.21	0.53	0.50	0.29
	8	4.51	3.78	0.27	0.30	0.16
Bequeló	3	6.34	4.39	0.98	0.62	0.36
	4	6.12	4.39	0.88	0.58	0.28
	5	7.87	5.85	1.09	0.77	0.15
	6	6.58	5.62	0.42	0.35	0.19
Quebracho	8	4.92	4.07	0.32	0.42	0.12
Tres Bocas	9	5.77	4.78	0.40	0.44	0.16

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 predicator 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

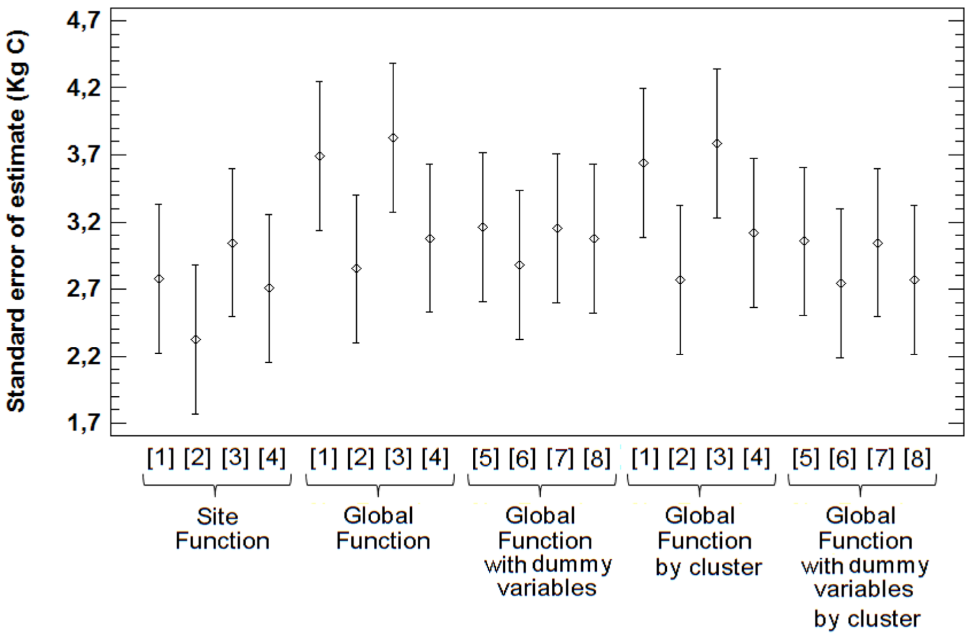

Figura 1. Dispersion of the standard error of estimate in Kg of carbon resulting from fitting functions.
Figure 1. Dispersão do erro padrão de estimativa (Kg C) resultado do ajuste das funções.

Tabela 3. Selected functions and associated goodness-of-fit measures by tree component and site.
Table 3. Funções escolhidas e indicadores do ajuste por componente e local.

Tree component	Site	Function	Adj-R²#	SEE (Kg C)	CV¥
Total above-ground	Algorta	$0{,}0329305\ DAP^{1{,}82840}h^{0{,}73382}$	96.85	3.78	0.05
	Bequeló	$0{,}0331501\ DAP^{1{,}90493}h^{0{,}61808}$	93.51	5.26	0.07
	Quebracho	$0{,}1055480\ DAP^{2{,}18118}$	97.83	4.07	0.04
	Tres Bocas	$0{,}0014145\ DAP^{2{,}10362}h^{1{,}51316}$	96.94	6.00	0.05
Bole	Algorta	$0{,}0167066\ DAP^{1{,}75580}h^{0{,}97605}$	95.04	4.02	0.07
	Bequeló	$0{,}0086058\ DAP^{1{,}51370}h^{1{,}41496}$	95.41	3.68	0.06
	Quebracho	$0{,}0490756\ DAP^{2{,}01132}h^{0{,}36214}$	98.09	3.17	0.04
	Tres Bocas	$0{,}0003891\ DAP^{1{,}59768}h^{2{,}36873}$	97.49	4.41	0.04
Leaves	Algorta	$0{,}0036656\ DAP^{2{,}40989}$	76.10	0.87	0.17
	Bequeló	$0{,}0921138\ DAP^{3{,}37537}h^{-2{,}08146}$	72.65	1.29	0.18
	Quebracho	$0{,}0073597\ DAP^{2{,}16159}$	81.40	0.87	0.16
	Tres Bocas	$0{,}0003698\ DAP^{3{,}20620}$	81.02	1.22	0.16
Live branches	Algorta	$0{,}0053832\ DAP^{2{,}27590}$	64.46	1.06	0.18
	Bequeló	$0{,}0109327\ DAP^{4{,}52262}h^{-2{,}63592}$	58.63	1.47	0.25
	Quebracho	$0{,}6407690\ DAP^{3{,}53542}h^{-2{,}79051}$	80.64	1.26	0.15
	Tres Bocas	$0{,}0000037\ DAP^{4{,}76555}$	86.70	1.29	0.13
Dead branches	Algorta	$0{,}2490690\ DAP^{0{,}67952}$	25.49	0.62	0.18
	Bequeló	$0{,}0850735\ DAP^{1{,}24975}h^{-0{,}30573}$	31.61	0.48	0.18
	Quebracho	$0{,}0605768\ DAP^{3{,}66268}h^{-2{,}53646}$	75.67	0.42	0.18
	Tres Bocas	$0{,}0044884\ DAP^{2{,}04389}$	45.61	0.83	0.23

\# indicates the adjusted R^2 to account for a different number of variables. ¥ indicates coefficient of variation (%) calculated as the SEE divided by the mean carbon absorption by tree component in each site.

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 R^2 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 R^2 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)

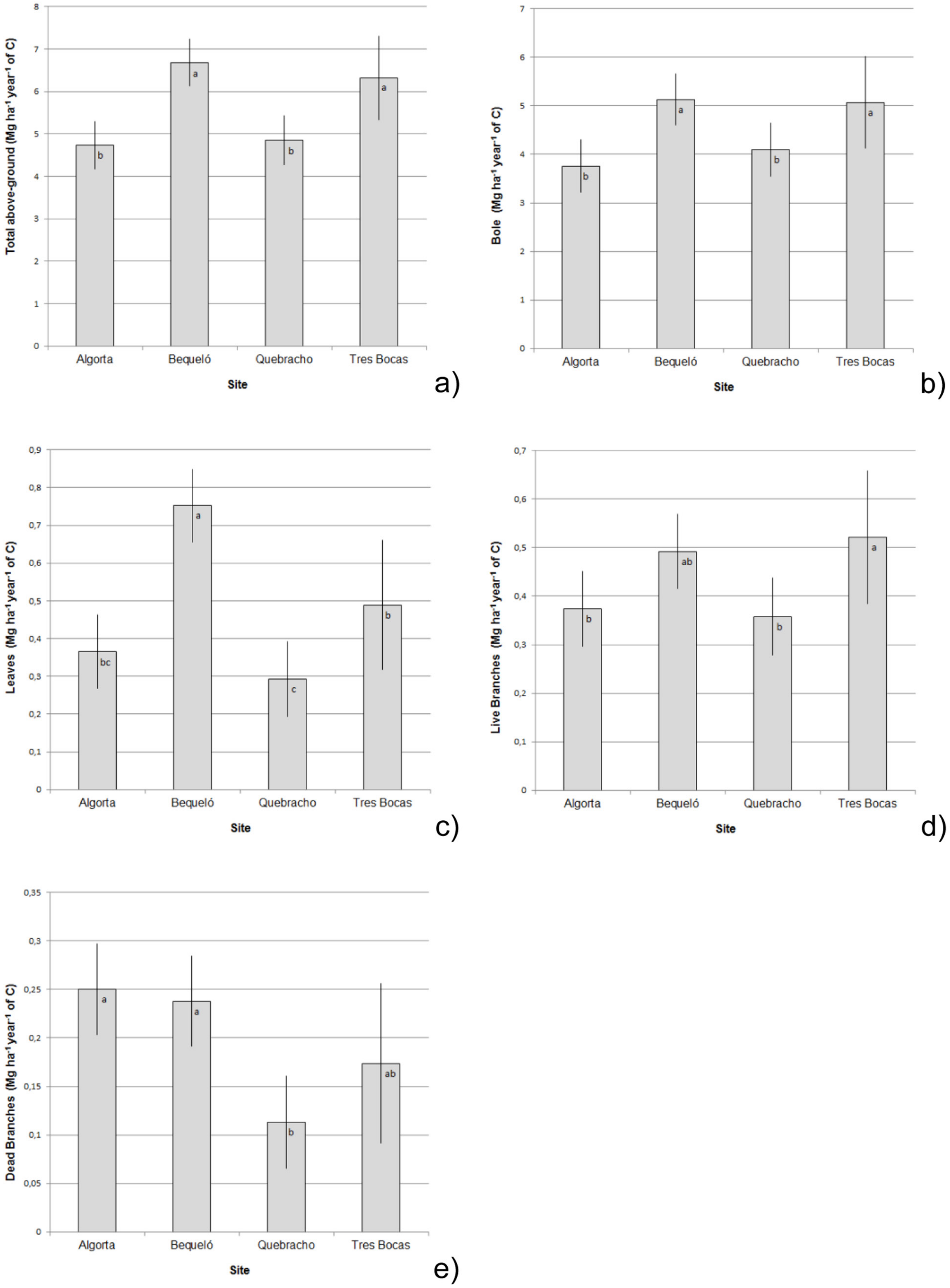

Figura 2. Duncan's multiple range test of the MAI carbon absorption (Mg ha^{-1} $year^{-1}$ of C) a) total above-ground, b) Bole, c) Leaves, d) Live Branches and e) Dead Branches.

Figure 2. Teste de comparação múltipla de Duncan do IMA do carbono absorvido (Mg ha^{-1} $year^{-1}$ de C) a) Total aéreo b) fuste c) folhas, d) galhos verdes e e) galhos secos.

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

BOSSI, J.; FERRANDO, L.; MONTAÑA, J.; CAMPAL, N.; MORALES, H.; GANCIO, F.; SCHIPILOV, A.; PIÑEIRO, D.; SPRECHMAN. P. **Carta geológica del Uruguay a escala 1:500.000.** Montevideo: Geoeditores SRL. 1998.

BRAÑAS, J.; GONZÁLEZ-RÍO, F.; MERINO, A. Contenido y distribución de nutrientes en plantaciones de *Eucalyptus globulus* del noroeste de la península Ibérica. **Investigacion Agraria. Sistemas y Recursos Forestales**, Madrid, v. 9, n. 2, p. 317–335, 2000.

CARRASCO-LETELIER, L.; EGUREN, G.; CASTIÑEIRA, C.; PARRA, O.; PANARIO, D. Preliminary study of prairies forested with*Eucalyptus* sp. at the northwestern Uruguayan soils. **Environmental Pollution**, London, v. 127, n. 1, p. 49–55, 2004.

CORREIA, A. C.; TOMÉ, M.; PACHECO, C. A.; FAIAS, S.; DIAS, A. C.; FREIRE, J.; CARVALHO, P. O.; PEREIRA, J. S. Biomass allometry and carbon factors for a Mediterranean pine (*Pinus pinea* L.) in Portugal. **Forest Systems**, Madrid, v. 19, n. 3, p. 418–433, 2010.

CRUZ, G.; MUNKA, C.; PEDOCCHI, R. Caracterización agroclimática de la región litoral centro oeste de la República Oriental del Uruguay. **Agrociencia**, Montevideo, v. 4, n. 1, p. 87–92, 2000.

DUNCAN, D. B. Multiple range and multiple F tests. **Biometrics**, Raleigh, v. 11, n.1, p. 1–42. 1955.

EAV, B.; BIRDSEY, R.; HEATH, L. The Kyoto Protocol and Forestry Practices in the United States. In: IUFRO WORLD CONGRESS, 21, 2000, Kuala Lumpur. **Proceedings…** Viena: IUFRO, 2000. v. 1, p. 566–576.

EBUY, J.; LOKOMBE J. P.; PONETTE, Q.; SONWA, D.; PICARD, N. Allometric equation for predicting Aboveground biomass of three tree species. **Journal of Tropical Forest Science**, Kepong, v. 23, n. 2, p. 125–132, 2011.

EVERITT, B. S.; LANDAU, S.; LEESE, M.; STAHL, D. **Cluster analysis**. 5.ed. London: John Wiley & Sons, 2011. 330 p.

GAYOSO, J.; GUERRA, J.; ALARCÓN, D. **Medición de la capacidad de captura de carbono en bosques de Chile y promoción en el mercado mundial. Inventario de Biomasa y Contabilidad de Carbono**. Valdivia, 2002. Disponível em: <http://www.uach.cl/procarbono/Documentos/Informe%20Tecnico%20Inventario.PDF>. Acesso em: 5 maio 2012. (Informe Técnico).

GIBBS, H.; BROWN, S.; NILES, J.; FOLEY, J. Monitoring and estimating tropical forest carbon stocks: making REDD a reality.**Environmental Research Letters**, v. 2, n. 4, p.1–13. 2007.

GUJARATI, D. **Econometria**. 2.ed. México: McGraw-Hill, 1996. 597 p.

HORNER, G.; BAKER, P.; MAC NALLY, R.; CUNNINGHAM, S.; THOMSON, J.; HAMILTON, F. Forest structure, habitat and carbon benefits from thinning floodplain forests: Managing early stand density makes a difference. **Forest Ecology and Management**, Amsterdam, v. 259, n. 3, p. 286–293. 2010.

HUNTER, I. Above ground biomass and nutrient uptake of three tree species (*Eucalyptus camaldulesis*, *Eucalyptus grandis* and*Dalbergia sissoo*) as affected by irrigation and fertilizer, at 3 years of age, in southern India. **Forest Ecology and Management**, Amsterdam, v. 144, n. 1-3, p. 189–200. 2001.

IPCC . **Climate Change 2007:** Report of the Intergovernmental Panel on Climate Change. Cambridge : Cambridge University Press, 2007.

JOKELA, E.; MARTIN, T. Effects of ontogeny and soil nutrient supply on production, allocation, and leaf area efficiency in loblolly and slash pine stands. **Canadian Journal of Forest Research**, Ottawa, v. 30, n. 10, p. 1511–1524. 2000.

KURZ, W. A.; DYMOND, C. C.; WHITE, T. M.; STINSON, G.; SHAW, C. H.; RAMPLEY, G. J.; SMYTH, C.; SIMPSON, B. N.; NEILSON, E. T.; TROFYMOW, J. A.; METSARANTA, J.; APPS, M. J. CBM-CFS3: a model of carbon-dynamics in forestry and land-used change implementing IPCC standards. **Ecological Modelling**, Kidlington, v. 220, n. 4, p. 480–504. 2009.

LEVENE, H. Robust tests for equality of variances. In: OLKIN, I. et al. (Ed.), **Contributions to probability and statistics**: Essays in Honor of Harold Hotelling. Menlo Park: Stanford University Press, 1960. p. 278–292.

LISKI, J.; PUSSINEN, A.; PINGOUD, K.; MÄKIPÄÄ, R.; KARJALAINEN, T. Which rotation length is favourable to carbon sequestration? **Canadian Journal of Forest Research**, Ottawa, v. 31, n. 11, p. 2004–2013. 2001.

LOZA-BALBUENA, I. Impacto del mercado del carbono en la performance económica de proyectos forestales: estudio de caso para*Pinus taeda* en Uruguay. In: SIMPOSIO INTERNACIONAL MEDICIÓN Y MONITOREO DE LA CAPTURA DE CARBONO EN ECOSISTEMAS FORESTALES, 2001, Valdivia, **Actas…** Valdivia, 2001. p. 1-16.

MARQUARDT, D. W. An algorithm for least-squares estimation of non-linear parameters. **Journal of the Society for Industrial and Applied Mathematics**, Philadelphia, v. 11, n. 2, p. 431–441. 1963.

MGAP - MINISTERIO DE GANADERÍA, AGRICULTURA Y PESCA. Disponível em: <http://www.mgap.gub.uy/portal/hgxpp001.aspx?7,20,441,O,S,0,MNU;E;134;2;MNU>. Acesso em: 5 maio 2012.

MIEHLE, P.; LIVESLEY, S. J.; FEIKEMA, P. M.; LI, C.; ARNDT, S. K.; Assessing productivity and carbon sequestration capacity of *Eucalyptus globulus* plantations using the process model Forest-DNDC: Calibration and validation. **Ecological Modelling,**Kidlington, v. 192, n. 1-2, p. 83–94. 2006.

MONTAGU, K.; DÜTTMER, K.; BARTON, C.; COWIE, A. Developing general allometric relationships for regional estimates of carbon sequestration—an example using *Eucalyptus pilularis* from seven contrasting sites. **Forest Ecology and Management**, Amsterdam, v. 204, n. 1, p. 115–129. 2005.

MORAS, G. **Tablas de volumen de *Eucalyptus globlulus* ssp. *globulus* al sur del Río Negro**. 2010, 110 p. Dissertação (Mestrado en Ciencias Agrarias). Universidad de la República, Montevideo, 2010.

MUÑOZ, F.; RUBILAR, R.; ESPINOSA, M.; CANCINO, J.; TORO, J.; HERRERA, M. The effect of pruning and thinning on above ground aerial biomass of *Eucalyptus nitens* (Deane & Maiden) Maiden. **Forest Ecology and Management**, Amsterdam, v. 255, n. 3-4, p. 365–373. 2008.

NAIDU, S.; DELUCIA, E.; THOMAS, R. Contrasting patterns of biomass allocation in dominant and suppressed loblolly pine.**Canadian Journal of Forest Research**, Ottawa, v. 28, n. 8, p. 1116–1124. 1998.

OLIVER, G. R.; BEETS, P. N.; PEARCE, S. H.; GRAHAM, J. D.; GARRETT, L. G.; Carbon accumulation in two *Pinus radiata*stands in the North Island of New Zealand. **New Zealand Journal of Forestry Science**, Rotorua, v. 41, p. 71–86. 2011.

PARRESOL, B. R. Assessing Tree and Stand Biomass: A Review with Examples and Critical Comparisons. **Forest Science**, Bethesda, v. 45, n. 4, p. 573–593. 1999.

PAUL, K. I.; JACOBSEN, K.; KOUL, V.; LEPPERT, P.; SMITH, J. Predicting growth and sequestration of carbon by plantations growing in regions of low-rainfall in southern Australia. **Forest Ecology and Management**, Amsterdam, v. 254, n. 2, p. 205–216. 2008.

PÉREZ-CRUZADO, C.; MERINO, A.; RODRÍGUEZ-SOALLEIRO, R. A management tool for estimating bioenergy production and carbon sequestration in *Eucalyptus globulus* and *Eucalyptus nitens* grown as short rotation woody crops in north-west Spain. **Biomass and Bioenergy,** Oxford, v. 35, n. 7, p. 2839–2851. 2011.

PÉREZ-CRUZADO, C.; RODRÍGUEZ-SOALLEIRO, R. Improvement in accuracy of aboveground biomass estimation in *Eucalyptus nitens* plantations: Effect of bole sampling intensity and explanatory variables. **Forest Ecology and Management**, Amsterdam, v. 261, n. 11, p. 2016–2028. 2011.

POPE, P.; GRANEY, D. Family differences influence the aboveground biomass of loblolly pine plantations. **USDA Forest Service SO Research Paper**, New Orleans, n. 155, p. 1-6, 1979.

RETZLAFF, W.; HANDEST, J.; O'MALLEY, D.; MCKEAND, S.; TOPA, M. Whole-tree biomass and carbon allocation of juvenile trees of loblolly pine (*Pinus taeda*): influence of genetics and fertilization. **Canadian Journal of Forest Research**, Ottawa, v. 31, n. 6, p. 960–970. 2001.

SANDS, P.; RAWLINS, W.; BATTAGLIA, M. Use of a simple plantation productivity model to study the profitability of irrigated*Eucalyptus globulus*. **Ecological Modelling**, Kidlington, v. 177, n. 1, p. 125–141. 1999.

SCHUMACHER, M.; WITSCHORECK, R. Inventario de carbono em povoamento de *Eucalyptus* ssp. nas propiedades fumageiras do sul do Brasil: "um estudo de caso". In: SIMPÓSIO LATINO AMERICANO DE FIXAÇÃO DE CARBONO, 2., 2004, Curitiba. **Anais...** Curitiba: FUPEF, 2004. p. 111–124.

SHAPIRO, S. S.; WILK, M. B. An analysis of variance test for normality (complete samples). **Biometrika**, Cambridge, v. 52, n. 3–4, p. 591–611. 1965.

SOMOGYI, Z.; CIENCIALA, E.; MÄKIPÄÄ, R.; MUUKKONEN, P.; LEHTONEN, A.; WEISS, P. Indirect methods of large-scale forest biomass estimation. **European Journal of Forest Research**, Berlin, v. 126, n. 2, p. 197–207. 2007.

SPECHT, A.; WEST, P. W.; Estimation of biomass and sequestered carbon on farm forest plantations in northern New South Wales, Australia. **Biomass and Bioenergy**, Oxford, v. 25, n. 4, p. 363–379. 2003.

STAPE, J. L.; BINKLEY, D.; JACOB, W.; TAKAHASHI, E. A twin-plot approach to determine nutrient limitation and potential productivity in *Eucalyptus* plantations at landscape scales in Brazil. **Forest Ecology and Management**, Amsterdam, v. 223, n. 1-3, p. 358–362. 2006.

VALERO, E.; SANS, C.; PICOS, M.; SORIA, L.; ESCUDERO, R.; IRISITY, F.; MORAS, G.; CARABALLO, P.; BARCIA, G. Comparación de ecuaciones de biomasa aérea para *Eucalyptus globulus* en Galicia y Uruguay. Aplicación para la estimación de la fijación de carbono en Eucaliptares. In: SIMPOSIO IBEROAMERICANO DE *EUCALYPTUS GLOBULUS*, 2., 2006, Pontevedra.**Actas…** Pontevedra: Univesidad de Vigo, 2006.

VALLEJOS, O.; SANQUETTA, C.; MENDOZA, M. Contenido de carbono de *Pinus taeda* L. según densidad de plantación, Estado de Paraná, Brasil. In: CONGRESO FORESTAL LATINOAMERICANO, BIENES Y SERVICIOS DEL BOSQUE, FUENTE DE DESARROLLO SOSTENIBLE, 2., 2002, Guatemala, **Actas…** Guatemala, 2002. p. 532–543.

VERWIJST, T.; TELENIUS, B. Biomass estimation procedures in short rotation forestry. **Forest Ecology and Management**, Amsterdam, v. 121, n. 1, p. 137–146. 1999.

WANG, J.; ZHANG, C.; XIA, F.; ZHAO, X.; WU, L.; VAN GADOW, K. Biomass structure and allometry of *Abies nephrolepis*(Maxim) in Northest China. **Silva Fennica**, Vantaa, v. 45, n. 2, p. 211–226. 2011.

ZIANIS, D.; MENCUCCINI, M. On simplifying allometric analyses of forest biomass. **Forest Ecology and Management**, Amsterdam, v. 187, n. 2-3, p. 311–332. 2004.

ZIANIS, D.; XANTHOPOULOS, G.; KALABOKIDIS, K.; KAZAKIS, G.; GHOSN, D.; ROUSSOU, O. Allometric equations for aboveground biomass estimation by size class for *Pinus brutia* Ten. trees growing in North and South Aegean Islands, Greece. **European Journal of Forest Research**, Berlin, v. 130, n. 2, p.145–160. 2011.

Recebido em 13/03/2013
Aceito para publicação em 27/11/2013