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Allometric models for estimating aboveground biomass in tree sprouts of three dendroenergetic crops

Abstract: Recurrent problems have been observed for biomass measurement in tree sprouts, mainly due to differences in patterns of biomass distribution and the bias generated by using models for mature trees. The objective of this research was to evaluate models to estimate aboveground biomass in sprouts from two-year-old stumps of Short Rotation Woody Crops (SRWC) used for energetic purposes.

The study was conducted in Central Chile (Bío-Bío region) under a complete block design and four replications. Three plant species were included: *Eucalyptus globulus, E. denticulata,* and *Acacia dealbata,* established in three population densities (5,000, 10,000 and 15,000 trees per ha). Two groups of nonlinear models were used on three independent variables: root collar diameter (squared mean of two dominant stems), height (mean of two dominant stems) and number of epicormic stems.

In the allometric model, the total aboveground biomass and the aboveground biomass by component were explained as the product of the mean square of the root collar diameter, mean height of the two dominant new sprouts and total number of epicormic sprouts as the predictive variable. Values of coefficient of determination (R^2) ranged from 0.78 to 0.95 and RMSE ranged from 168 to 913 g. The species of *E. globulus* showed higher RMSE for biomass estimation in the all components except the branch component. The inclusion of dummy variables to identify the differences in each parameter of the models explained the seasonality of the biomass accumulation in tree sprouts at 10, 21, and 31 months of age, improving the model goodness of fit RMSE by 27%.

Accurate prediction of sprouts aboveground biomass was obtained by the models only evaluating the two dominant epicormic sprouts in the stump, avoiding the need of individual sprouts evaluation or using destructive methods for biomass measurement.

Keywords: bio-energy, short rotation, *Eucalyptus globulus, Eucalyptus denticulata, Acacia dealbata,* dummy variables

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Introduction

The growth of the world's economy presents an important challenge to the future demand of energy. Renewable energy states about 13.3% of the world's total primary energy, and it is believed that it will play an increasingly important role in energy supplies in both developing and developed societies in the future (Erakhrumen, 2018). Biofuels represent almost 80% of total renewable energy supplying more energy than nuclear sources, and about four times as much as hydropower, wind, solar, and geothermal energy combined (FAO, 2007). About 75% of biofuels are derived from wood fuel (Erakhrumen, 2018; FAO, 2007). Short Rotation Woody Crops (SRWC) used for energy purposes are a viable alternative to increase and diversify the country's energy supply (Peña Sandoval, 2010). In Chile, there are approximately 1.8 million hectares of land considered as rainfed soil. This land with serious restrictions for growth (i.e. rainfall is concentrated in 3 or 4 winter months and has a drought period of 7 to 9 months), may be used to cultivate energetic crops using tree species specially adapted for this condition (Santelices et al., 2013).

The establishment of short rotation crops for biomass production could provide environmental and economic benefits to the rural communities, and for society in general (Sawin et al., 2013). Forest biomass is a source of renewable energy that may be sustainably managed (Richardson & Verwijst, 2007). The sustainability of dendroenergetic crops depends on several factors: the operations and economy of the production of raw materials, the site productivity, and improvements in forestry practices such as thinning young stands, crop tree management or release, and girdling (Richardson & Verwijst, 2007). Vegetal biomass is generally considered as a green energy source, nevertheless, Choi & Manousiouthakis (2020) founded that use of biomass as a fuel may result in a higher CO_2 atmospheric concentration than fossil carbon burning, depending on the rate of burning and reforestation intensity. Many species are adequate for the production of large volumes of biomass if they are managed as short rotation forestry crops. The most important dendroenergetic taxa worldwide are eucalypts (*Eucalyptus globulus, E. nitens, E. denticulata*) (Camps & Marcos, 2002), willows (*Salix* spp), poplars (*Populus* spp), paulownia (*Paulownia* spp) and acacias (*Acacia dealbata, A. melanoxylon, A. retinodes*). These species are important as dendroenergetic crops due to their high growth rate and easy sprouting (Hoogwijk et al., 2005). This last characteristic has a high relevance because several short rotation cycles may be the result of only one initial establishment, avoiding the need to replant (Sixto et al., 2007).

The short rotation species are cultivated under a scrub-land system, ranging from one to 15 years and a high-density planting. This results in a higher yield per area unit comparing to a single tree planting of the same age as the trunk/stump, where the new sprouts are developing (De-Souza et al., 2016). This should allow for an optimal usage of the natural resources and for an ecological and economical betterment through the implementation of physical and biological knowledge, (Landsberg et al., 1997). To quantify the performance of dendroenergetic crops, certain functions are necessary to estimate the aboveground biomass. In traditional plantations, established for lumber or wood pulp operations, it is common to use allometric models which are based on correlations between biomass and morphological characteristics (basal diameter or area, height, canopy diameter, or canopy volume. In general, this is one of the best options for predicting and quantifying biomass in single tree type plantations (Hauk et al., 2014). However, in a scrub-land system as is the case for dendroenergetic crops, starting with the second crop cycle, many sprouts emerge from each stump forming multiple trunk individuals. Moreover allometric biomass allocation theory predicts that leaf biomass (ML) scaled isometrically with stem (MS) and root (MR) biomass, and thus above-ground biomass (leaf and stem) (MA) and root (MR) scaled nearly isometrically with below-ground biomass (root) for tree seedlings across a wide diversity of taxa. Furthermore, prior studies also imply that scaling constant should vary with species (Cheng et al., 2014). This presents interesting challenges when trying to estimate the total aboveground biomass, or by components when needed.

Acacia dealbata is a large shrub to tall tree with an erect stem usually ranging in height from two-15 m; it often is seen as a spreading shrub but where space allows it has a rounded crown; bark is brown grey to dark grey, often mottled white (due to lichen growth). *Eucalyptus denticulata* is a tree up to 60 m high; bark persistent on lower trunk, grey to grey-brown, fibrous-flaky, smooth above, white, grey or yellow, shedding in long ribbons; tolerates poorly drained upland areas; its growth rate is up to 24 m^3 ha^{-1} $year^{-1}$. *Eucalyptus globulus* varies from a multi-stemmed shrub on exposed sites, to a medium-sized woodland tree up to 20 m tall, to a very tall tree up to 70–80 m tall with a large open crown. Hence the interest in conducting this research study on how to evaluate (fit) the models for estimating the aboveground biomass in the new sprouts at the trunk/stump level for *Acacia dealbata, Eucalyptus denticulata* and *Eucalyptus globulus* in two years old stumps. It is hypothesized that exponential typical model for biomass estimation in single-stem trees is efficient in sprouting dendroenergetic crops.

Materials and methods

Study design

This research was performed at La Aguada property located at Yumbel commune in the Bio-Bío region (37°11'22.94"S, 72°26'04.08"W) in August, 2010. The land is sandy, with soils from alluvial provenance, deep and underdeveloped, derived from black volcanic sands, with a basaltic-andesitic origin, with a coarse composition in its profile and moderately coarse on the surface. The climate is sub-humid, annual mean temperature is 19 °C; the annual average rainfall is 1,093 mm (Novoa et al., 1989).

The test was implemented following a random complete block design with three repetitions. Each segment block was a square of 110 m per side (12,100 m²), conformed by four quadrants, each consisting of nine study plots of 18 m on each side (324 m²). Each study plot, in turn, constituted a 0.4 m wide buffer zone to prevent the fringe effect and a square core of 30 useful stumps in order to observe and evaluate the growth of the crop. Each quadrant included nine treatments, which are generated from the combination of three species (*Acacia dealbata, Eucalyptus denticulata, Eucalyptus globulus*) in three plantation densities (5,000, 10,000 and 15,000 trees ha). Each quadrant corresponded to one of four cutting frequencies (every one, two, three and four years, starting with the first intervention when the crop was two years old. (Fig. 1). It was assumed all observations are independent to make formulas easier in implementation.

Measurement of the variables

The quadrant has harvested in December 2012, corresponding to a bi-annual cutting frequency. As of yet, three measurements have been carried out with the purpose of evaluating the population dynamics of the new sprouting and the aboveground biomass production in this quadrant: October 2013, September 2014 and September 2015. Each time, the number of new sprouting and of adventitious sprouts at each stump was registered. The type of new sprouting was determined based on its physical characteristics and position on the stump. Those that sprouted on the crown of the trunk/stump and in a horizontal position were identified as adventitious and those better joined to the mother plant (stump) and in a vertical position were identified as sprouts. For the dendrometric measurements, the two main new sprouting of each stump were identified and each measured for the following: total height, crown diameter, diameter at root collar (DRC) and diameter at breast height (DBH), when the new shoots exceeded the height of 1.3 m.

The data used to develop the aboveground biomass functions were gathered on the same dates the measurements were taken and are the result of a destructive biomass study from three stumps selected. The stumps collected comply with the diametric distribution (D) and total height. These trunks/stumps were cut at 0.1 m above ground level and then transported and stored at 4 °C. At the laboratory, the shoots from each stump were separated and counted according to their category and their total height was measured, as well as the diameter along the length of the trunk (0.10, 0.50, 1.0 and 1.30 m). Afterwards, the components (stem, branch and leaves) of each new shoot were weigthed in fresh state with a digital scale with a precision of 0.01 g. In order to determine the dry weight, samples were taken from each component of up to 500 g, and then dried in a stove at 105 °C, up to the constant mass (Brown, 1999; Schlegel et al., 2000). Afterwards,
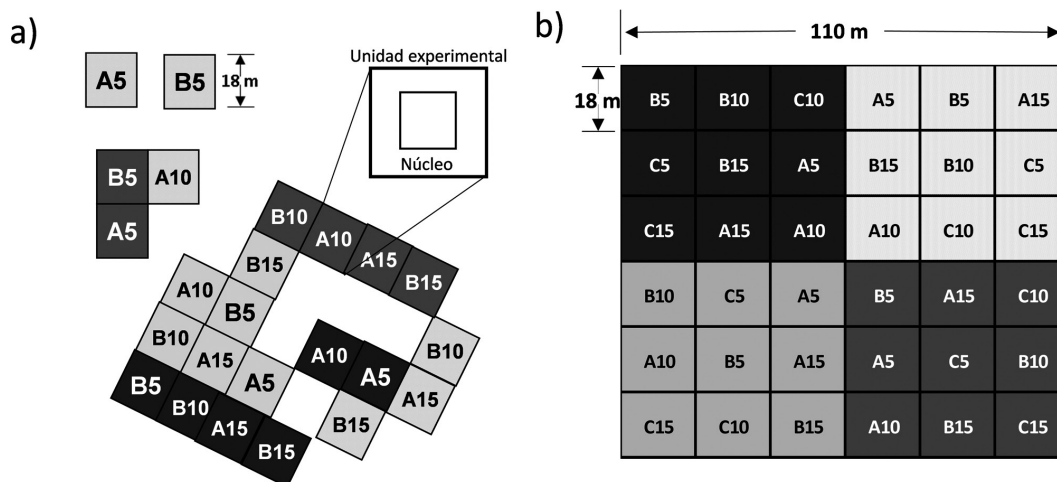

Fig. 1. Description of a trial block. Each color represents a quadrant and a cutting frequency (1, 2, 3 and 4 years); letters represent the species (A – *Acacia dealbata*, B – *Eucalyptus denticulata* and C – *Eucalyptus globulus*) and numbers (5, 10 and 15 for 5,000, 10,000 and 15,00 ind. ha⁻¹, respectively) the density of the planting

from the ratio between dry and wet mass, the total dry aboveground biomass was calculated for each component from each stump. The total aboveground biomass for each stump was obtained by adding the aboveground biomass of all its components. In total, 63 trees of *A. dealbata*, 76 trees of *E. denticulata*, and 81 trees of *E. globulus* were analyzed.

Simple linear models have been used in the aboveground biomass modeling of crops on multiple tree trunks (Zeng & Tang, 2011; Wouokoue Taffo et al., 2018; Malakini et al., 2020); adding the sum of the square value of the diameter at root collar (*DRC*), the total height of each one of the shoots on the stump as independent variable. To this effect, an allometric model (Model 1) which is commonly used to estimate aboveground biomass was used to test three different sets of predictive variables: i) the product of the diameter squared times the height of the tallest new shoot ($DRC^2 \cdot H$); ii) the product of the average of the diameters squared, times the average height of the two main dominant new shoots ($\overline{DRC}^2 \cdot \overline{H}$); and iii) the product of the average diameters squared times the average height of the two main dominant new shoots, multiplied by the number of new sprouts ($\overline{DRC}^2 \cdot \overline{H} \cdot vp$). Also, two additional models were analyzed (Models 2 and 3), consisting of variants of this latter predictive variable. In these last two models, species and age effects were analyzed by incorporating *dummy* variables: dichotomous and quantitative, their range of values is small; they can take on only two quantitative values, (Jacobs & Cunia, 1980) (Models 4 and 5).

$$y_i = a_0 x_i^{b_1} \tag{1}$$

$$y_i = a_0 (\overline{DRC}^2 \cdot \overline{H})^{b_1} (vp)^{b_2} \tag{2}$$

$$y_i = a_0 (\overline{DRC}^2)^{b_1} (\overline{H}) (vp)^{b_2} \tag{3}$$

$$y_i = a_0 + \delta_{0_2} + \delta_{0_3} (\overline{DRC}^2 \cdot \overline{H})^{b_1 + b_{12} + b_{13}} (vp)^{b_2 + b_{22} + b_{23}} \tag{4}$$

$$y_i = a_0 + \delta_{0_2} + \delta_{0_3} (\overline{DRC}^2)^{b_1 + \delta_{12} + \delta_{13}} (\overline{H}) (vp)^{b_2 + \delta_{22} + \delta_{23}} \tag{5}$$

Where: y_i is the total aboveground biomass of the ith stump, x_i is the predictive variable of the ith stump, DRC^2 is the average squared root collar diameter of the two dominant shoots on the stump, H is the average height of the two dominant shoots on the stump, vp is the number of new shoots, a_0, b_1, b_2 are regression parameters; δ_{i_2} is the *dummy* variable associated with the age of 21 months, δ_{i_3} is the *dummy* variable associated with the age of 31 months.

The goodness-of-fit of the models was evaluated using the Root Mean Squared Error (RMSE).

$$\text{RMSE} = \sqrt{\frac{SS}{n - p}} \tag{6}$$

Where, SS is the sum of the residual squares (i.e. $\Sigma(y_i - \hat{y}_i)^2$), n is the total number of observations and p is the number of parameters in the model.

The Akaike Information Criterion (AIC) was used to select the best models, which is useful when comparing models that vary in the number of parameters. In estimating the amount of information lost by a model, AIC deals with the trade-off between the goodness of fit of the model and the simplicity of the model. In other words, AIC deals with both the risk of overfitting and the risk of underfitting.

$$AIC = n ln\left(\frac{SSE}{n}\right) + 2p \tag{7}$$

Where, n is the total number of observations, ln is the natural logarithm, SSE is the sum of squares of error p is the number of model parameters.

The adjustments to the models were performed using the NLIN Procedure and the statistical software SAS 9.2 (SAS Institute Inc., 2008).

Results

The count of new sprouts at 10, 21 and 31 months of growth allowed for the analysis of the population dynamics of new adventitious and type sprouts for each species, as well as, the planting density (Fig. 2). *A. dealbata* at ten months of growth with 15,000 trees per hectare, registered the highest number of new adventitious sprouts with an average value of eight with low and high extreme values of two and 37, respectively. However, over time, a significant reduction in this type of new sprouts was registered, i.e. six new sprouts at 21 months and three at 31 months. On the other hand, the number of new sprouts was constant over time, with an average value of four with low and high extreme values of one and six, respectively. *E. denticulata* at 10 months of growth showed an average value of five and seven new adventitious sprouts in the densities of 10,000 and 15,000 trees per ha respectively. Additionally, a strong variation was observed between stumps with maximum values of up to 25 new sprouts. This feature greatly decreased at 31 months of growth, up to 25% in adventitious sprouts and 40% in sprouts in all planting densities. With *E. globulus*, at 10 months and with 5,000 trees per ha, a larger number of new adventitious sprouts was observed, with an average of eight and a maximum of 36. At 21 and 31 months a considerable reduction was observed, with an average of three for both types of new sprouts.

In the three species, the total aboveground biomass, as well as by component, was better explained as the product between the average of the squared root collar diameter, the mean height of the two

dominant new shoots and the quantity of new shoots $(DRC|2 \cdot H \cdot vp)$. For the three species, all the parameters included in the allometric model (Model 1) were significant at 95% for estimating the total aboveground biomass and by component (Table 1).

RMSE ranged between 168 and 913 g. *E. globulus* showed a greater RMSE in the estimation of total aboveground biomass and on two of the components (stem and leaves). The statistics for the branches component in *A. dealbata* and *E. denticulata* showed a
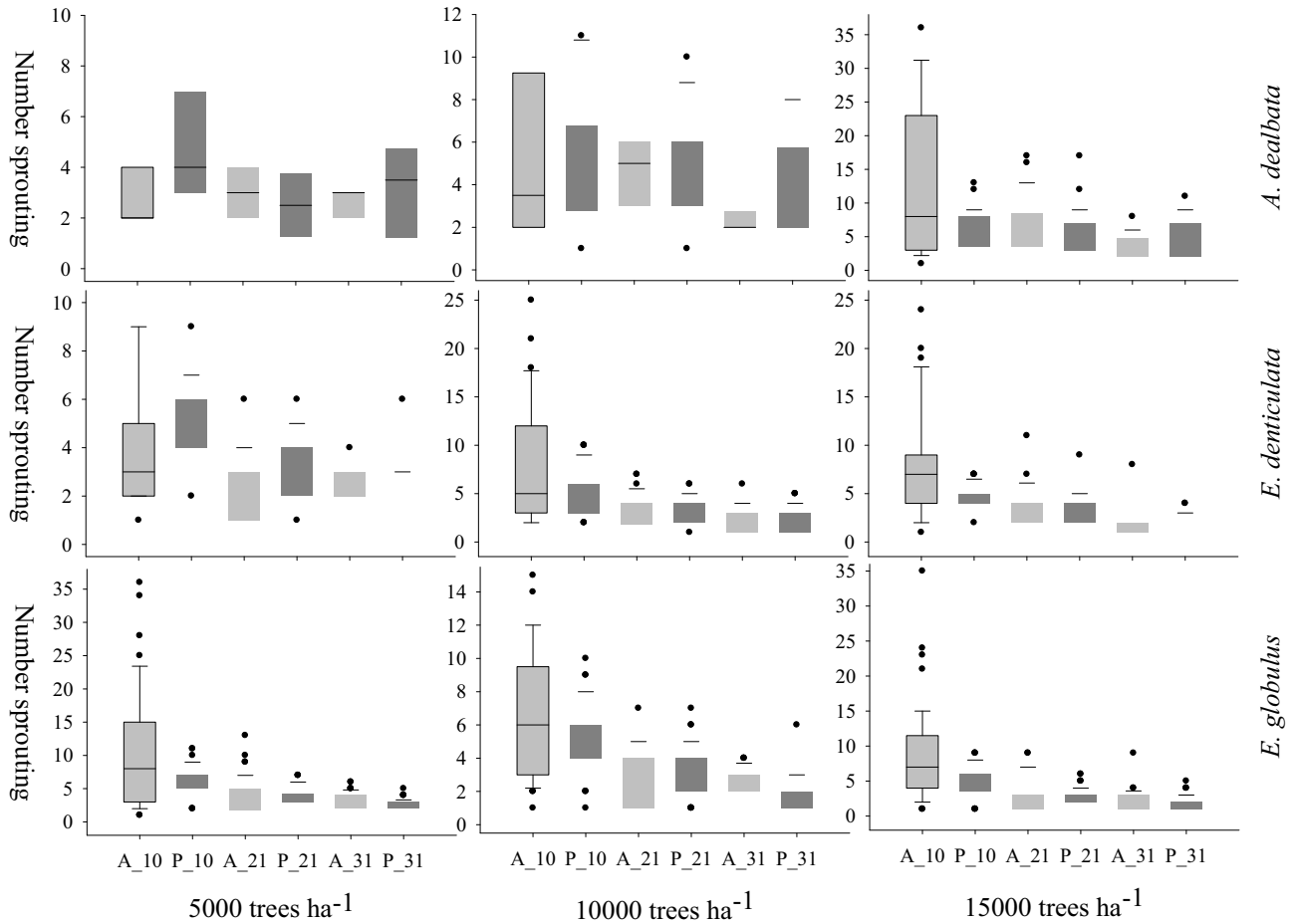

Fig. 2. Boxplot for the number of new adventitious (A) and water (P) sprouts in three ages (10, 21 and 31 months) in stumps of three plant species and planting densities. The rectangle or box boundaries represent 1st and 3rd quartiles, line within the box – median value; whiskers represent range of minimum and maximum without outliers, which are marked by points

Table 1. Estimated parameters and statistical values for goodness-of-fit of the allometric model (Model 1), for estimating total aboveground biomass and for components in shoots, by species

Species	Biomass	n	a_0	b_1	RMSE	AIC
A. dealbata	Total	63	2.3316*	0.7188**	690.32	825.7
	Stem	63	0.8258*	0.7712**	485.79	781.4
	Branches	63	1.2153*	0.6132**	185.68	660.2
	Leaves	63	0.5221*	0.7166**	224.64	684.2
E. denticulata	Total	76	5.5198*	0.6892**	880.85	1032.7
	Stem	76	1.8896*	0.7336**	626.39	980.8
	Branches	76	1.6124*	0.6377**	202.67	809.3
	Leaves	76	2.9643*	0.6284**	290.95	864.3
E. globulus	Total	81	2.0506*	0.7852**	913.76	1106.4
	Stem	81	0.6299*	0.8523**	758.01	1078.1
	Branches	81	0.4804*	0.7389**	168.98	833.0
	Leaves	81	2.6837*	0.6209**	313.81	933.3

Where, *n* is the sample size, , b_1, b_2 are the regression parameters, RMSE is the Root Mean Squared Error, the asterisks indicate the significance levels, i.e. * p < 0.05; ** p < 0.01.
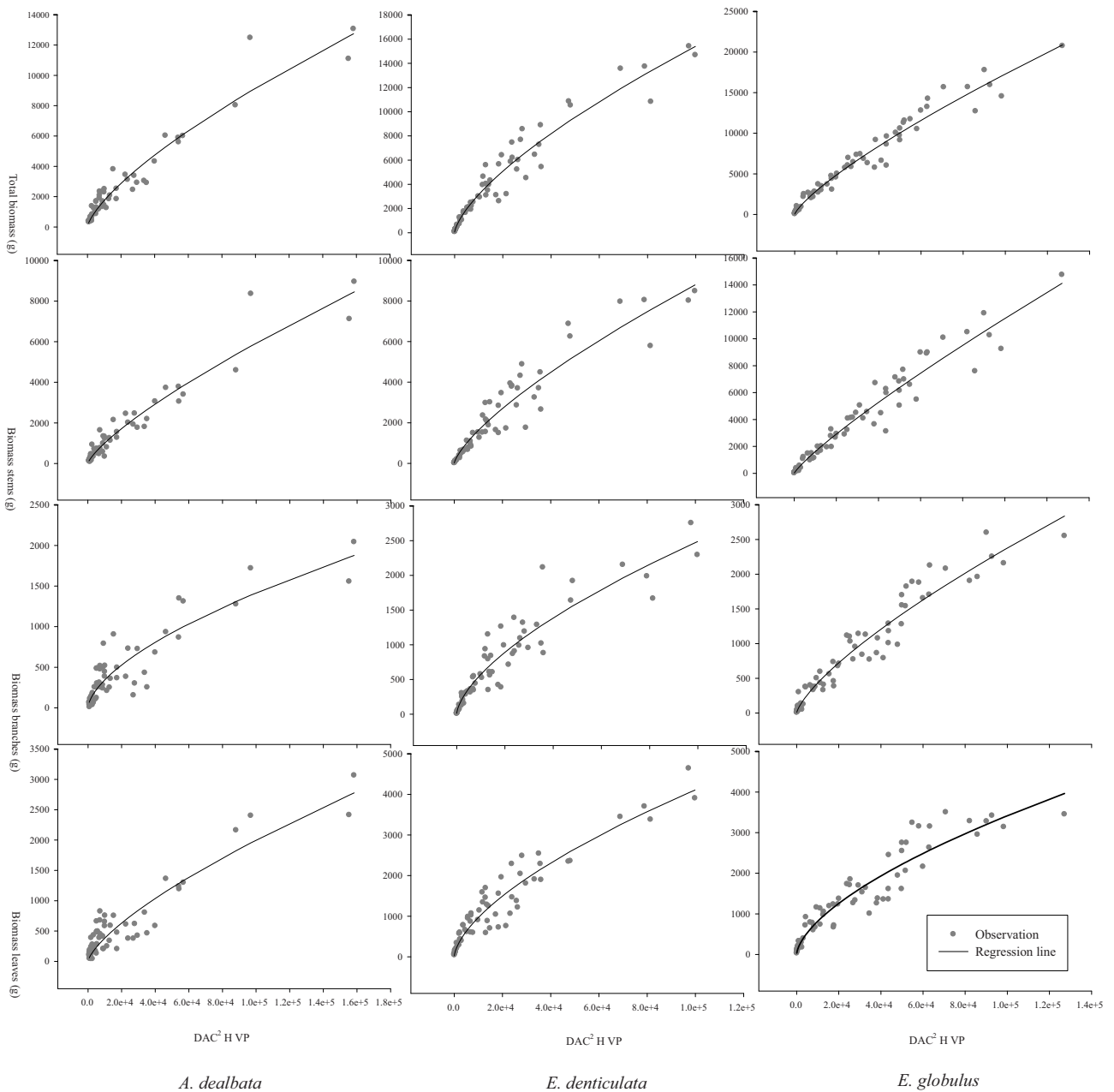
Fig. 3. Dispersion of the data observed from the total aboveground biomass and components (stem, branches and leaves) of the shoots and estimation line of the allometric model evaluated for each species

greater variation, followed by the leaves component (Table 1).

The tendency of the values for total aboveground biomass and by component, with respect to the predictive variable, was similar for the three species. Trends of aboveground biomass and its components, in relation to particular independent variable, were consistent among species studied. This is because in the combined analysis of the aboveground biomass on these three evaluation dates (10, 21 and 31 months) the passing of time allows the components to be more variable in their aboveground biomass. The foregoing could lead us to conclude that the regression parameters could belong to a single

function that would represent the three species and each component. However, in all three species and due to three different ages, the a_0 coefficient was the one that showed variation in the total aboveground biomass and components (Table 1 and Fig. 3).

Models 2 and 3 provided better adjustments than the allometric model (Model 1). Model 2 used for *A. dealbata* has three regression parameters, where the statistics for goodness-of-fit were similar to the allometric model, but when the models were compared using the AIC, it was less in these models, with values ranging from 656.8 to 812.8 (Table 2).

The evaluated model for estimating total aboveground biomass and by components for the

Eucalyptus species (Model 3) has a different structure than the one evaluated for *A. dealbata.* This is attributed to the type of plant growth ocurring in the shoots of each genus (*Eucalyptus* and *Acacia*). In this model, the statistics for goodness-of-fit were better than those from the allometric model, two of its parameters were of high significance ($\alpha = 0.01$) reducing its RMSE, in total aboveground biomass and its components (stem, branches and leaves) all compared with AIC (Table 3).

The joint analysis of the estimation of aboveground biomass in new shoots for the three evaluation dates 10, 21 and 31 months, was explained including dummy variables in order to identify the differences in each parameter for Models 4 and 5. For *A. dealbata* the model used for estimating total aboveground biomass and that for leaves component, showed significant differences ($\alpha = 0.05$) on all parameters (Table 4), (a_0) was different at 31 months of age (δ_{0_3}) and the other two parameters showed differences at age 21 months of age ($\delta_{1_2}, \delta_{2_2}$) (Model 8), yielding six

regression parameters within the model. All of them showed significant reduction of the RMSE (Table 4). This may explain why in these types of crops and in this species the leaves component is the one with the greatest variation over time. The stem component only showed differences on the slope at 21 months of age ($\delta_{1_2}, \delta_{2_2}$) remaining with five regression parameters (Model 9) and the branches component only showed differences in one parameter (b_2) at the age of 21 months (δ_{2_2}) (Model 10, Table 4).

$$y_{total,leaves} = a_0 + \delta_{0_3}(DRC^2 \cdot \overline{H})^{b_1 + \delta_{1_2}}(vp^{b_2 + \delta_{2_2}}) \qquad (8)$$

$$y_{stem} = a_0(\overline{DRC}^2 \cdot \overline{H})^{b_1 + \delta_{1_2}}(vp^{b_2 + \delta_{2_2}}) \qquad (9)$$

$$y_{branches} = a_0(DRC^2 \cdot \overline{H})^{b_1}(vp^{b_2 + \delta_{2_2}}) \qquad (10)$$

With *E. denticulata* the total aboveground biomass and the stem and branches components only showed significant differences on one of the parameters at 21 months of age (δ_{2_2}), resulting with four parameters

Table 2. Estimated parameters and statistical data for goodness-of-fit in Model 2, for the estimation of total aboveground biomass and components in shoots of *A. dealbata*

Biomass (y)	n	a_0	b_1	b_2	RMSE	AIC
Total	63	1.3238*	0.8050**	0.6025**	618.88	812.8
Stem	63	0.5095*	0.8436**	0.6779**	461.53	775.8
Branches	63	0.8326*	0.6835**	0.4741**	179.45	656.8
Leaves	63	0.4260*	0.7465**	0.6805**	219.69	678.1

Where, n is sample size, , b_1, b_2 are regression parameters, RMSE is the Root Mean Squared Error, and the asterisks indicate the significance levels, i.e. * p < 0.05; ** p < 0.01.

Table 3. Estimated parameters and statistical values for goodness-of-fit for Model 3, for estimating total aboveground biomass and components in shoots of *E. denticulata* and *E. globulus*

Biomass (y)	n	a_0	b_1	b_2	RMSE	AIC
Ed – total	76	5.1300*	0.6549**	0.5397**	678.93	994.1
Ed – stem	76	1.4636*	0.7448**	0.4872**	376.57	904.4
Ed – branches	76	1.4167*	0.5987**	0.4937**	188.62	799.4
Ed – leaves	76	3.6021*	0.5200**	0.6759**	317.86	878.7
Eg – total	81	2.0530*	0.7397**	0.7485**	807.21	1087.3
Eg – stem	81	0.7685*	0.8101**	0.7034**	558.38	1027.6
Eg – branches	81	0.4410*	0.6750**	0.8721**	176.29	840.8
Eg – leaves	81	1.9853*	0.5511**	0.8024**	354.32	953.9

Where, *Ed* is *E. denticulata*, *Eg* is *E. globulus*, *n* is sample size, , b_1, b_2 are the regression parameters, RMSE is the Root Mean Squared Error, and the asterisks indicate the significance levels, i.e. * p < 0.05; ** p < 0.01.

Table 4. Estimated parameters for Models 8, 9 and 10 using dummy variables to estimate total aboveground biomass and of components in new shoots of *A. dealbata*

Model	Biomass (y)	n	a_0	δ_{0_3}	b_1	δ_{1_2}	b_2	δ_{2_2}	RMSE
8	Total	63	1.2401*	−0.4575*	0.8893**	−0.0971*	0.4179**	0.2927**	486.77
9	Stem	63	0.5019*	–	0.8833**	0.0799*	0.4504**	0.4064**	372.90
10	Branches	63	0.5519*	–	0.7503**	–	0.2983**	0.1676*	161.20
8	Leaves	63	0.2911*	0.2039**	0.9492*	0.1573**	0.4463**	0.2646*	178.61

Where, y is the biomass, is the mean squared root collar diameter of the two dominant water shoots on the stump, is the mean height of the two dominant water shoots on the stump, vp is the number of new water shoots, n is the sample size, δ_i are the dummy variables and b_1, b_2 are the regression parameters, RMSE is the Root Mean Squared Error, and the asterisks indicate the significance levels, i.e. *p < 0.05; **p < 0.01.

Table 5. Estimated parameters for Models 11 and 12 using dummy variables to estimate total biomass and of the components in new shoots of *E. denticulata*

Model	Biomass (y)	n	a_0	b_1	δ_{1_2}	b_2	δ_{2_2}	RMSE
10	Total	76	7.4682*	0.6033**	–	0.6022**	−0.1058*	637.16
10	Stem	76	2.3237*	0.6832**	–	0.5468**	−0.1245*	346.94
10	Branches	76	1.9240*	0.5561**	–	0.5524**	−0.0969*	185.98
11	Leaves	76	3.8205*	0.4994**	0.1405*	0.7960**	−0.6871*	293.24

Where, y is the biomass, is the mean squared root collar diameter of the two dominant new water shoots on the trunk/stump, is the mean height of the two dominant new water shoots on the stump, vp is the number of new water sprouts, n is the sample size, δ_i are the dummy variables, are the regression parameters, RMSE is the Root Mean Squared Error, and the asterisks indicate the significance levels, i.e. *p < 0.05; **p < 0.01.

Table 6. Estimated parameters for Model 13 using dummy variables to estimate the total biomass and of its components in new shoots of *E. globulus*.

Biomass	n	a_0	b_1	δ_{1_3}	b_2	δ_{2_3}	RMSE
Total	81	1.7305**	0.8208**	−0.0687**	0.4109**	0.4539**	707.20
Stem	81	0.7127*	0.8677**	−0.0580*	0.4011**	0.4536**	465.76
Branches	81	0.3271*	0.8009**	−0.0986*	0.4058*	0.5695*	162.88
Leaves	81	1.4540*	0.6632**	−0.0785*	0.4296*	0.4074*	347.34

Where, y is the biomass, (DRC^2) is the mean squared root collar diameter of the two dominant new water shoots on the trunk/stump, is the mean height of the two dominant new water shoots on the stump, vp is the number of new water sprouts, n is the sample size, δ_i are the dummy variables, are the regression parameters, RMSE is the Root Mean Squared Error, and the asterisks indicate the significance levels, i.e. *p < 0.05; **p < 0.01.

improving the fit (Table 5). The leaves component yielded five regression parameters, showing significant differences in two of the parameters (b_1, b_2) at the same age corresponding to 21 months, (δ_{2_2}) (Model 11).

$$y_{total,stem,branches} = a_0(\overline{DRC^2})^{b_1}(\overline{H})(vp^{b_2+\delta_{2_2}}) \qquad (11)$$

$$y_{leaves} = a_0(\overline{DRC^2})^{b_1+\delta_{1_2}}(\overline{H})(vp^{b_2+\delta_{2_2}}) \qquad (12)$$

E. globulus also improved the adjustment or fit of its parameters with the incorporation of these types of variables, resulting in a model for estimating total aboveground biomass and its components (stem, branches and leaves), showing significant differences on two of its parameters at 31 months of age (δ_{1_3}, δ_{2_3}) (Table 6).

$$y = a_0(\overline{DRC^2})^{b_1+\delta_{1_3}}(\overline{H})(vp^{b_2+\delta_{2_3}}) \qquad (13)$$

Discussion

The number of adventitious and sprouts diminished over time due to competition and position of the sprouts on the stump (Fig. 2). Vita et al. (1997) evaluated the response of sprouts on *Acacia caven* (native to Chile) at different cutting heights from the ground level, registering that the adventitious sprouts were more abundant when the treatment cuts were low, and increased over time. A similar situation was found in this research at the initial development of adventitious new sprouts of *A. dealbata*,

although these diminished over time, unlike the sprouts which remained over time. The latter is attributed to the fact that the physiology and sprout production is of the cespitose type, where its new vertical sprouts, as well as the horizontal ones are not hindered in their growth and survival in comparison to eucalyptus where both adventitious and sprouts decrease over time (Fig. 2). Similar results with *E. globulus* were found by Villegas (2003), reporting that from the multiple new sprouts per bud, over time, only two or three showed rapid growth, affecting others in this manner. Geldres et al. (2004), studied the tendencies of strength and vigor in three *Eucalyptus* species, concluding that it is feasible to handle *E. globulus* starting from a sprout. They found that *E. viminalis* displays good sprouting capacity but reaches smaller dimensions and *E. regnans* was not a good alternative for a scrub land type environment. In our research, both eucalyptus (i.e. *E. denticulata* and *E. globulus*) showed similar patterns in the production of new sprouts (Fig. 2).

The allometric model has been used in research of short rotation crops to estimate the aboveground biomass by Liberloo et al. (2006) and Rock (2007) in *Populus tremula (L.)×P. tremuloides* (Michx.) (Astria), Vande Walle et al., (2007) in *Acer* spp., *Betula* spp., *Populus* spp and *Salix* spp., Avohou et al. (2011) in *Daniellia oliveri*, where researchers measured each shoot as a single stem, while others pruned the stump leaving one or two sprouts, on which the diameter of the stem (DBH) was measured as a predictive variable (x), with the purpose of finding the best fit in the model. For example, Hytönen et al.

(1995), Ruiz-Peinado et al. (2011), Gómez-García et al. (2014), Gómez-García (2013) and Albert et al. (2014), used allometric models to evaluate biomass production using pseudovolume, which provides single predictor, which avoids effect of variance inflation connected with predictors collinearity. The majority of these studies reported a coefficient of determination (R^2) greater than 0.85 in the estimation of aboveground biomass (Ríos-Saucedo et al., 2016).

The strategy adopted in this study to estimate aboveground biomass and by component in new sprouts on two year old stumps – without measuring each shoot as an individual tree and without pruning the stump, but only using the two dominant new shoots as predictive variable, the root collar diameter (*DRC*), the total height (*H*) and counting the new sprouts (*vp*),attained good fits with the allometric model on the three species studied, for total aboveground biomass and also for its components (stem, branches and leaves) (Table 1).

The models proved to be better than the allometric model, when utilizing a different number of parameters with a different structure for the predictive variable for the three species (*A. dealbata*, *E. denticulata* and *E. globulus*). Similar results to those reported by Álvarez-González et al. (2005), when they modeled the production of aboveground biomass in *Eucalyptus globulus* and *Pinus pinaster* using the simple linear model where; represents the independent variables used, represents the parameters of the model to be estimated and is the error of the model, resulting in different numbers of parameters and predictive variables in the model of the species studied. Reporting a coefficient of determination (R^2) of up to 0.97 in *Eucalyptus globulus* and 0.91 in *Pinus pinaster* in the estimation of aboveground biomass. For the bias correction of the logarithmic transformation, the correction factor proposed by Finney (1941) was applied, concluding that the model is effective for estimating aboveground and undreground biomass in *E. robusta*, by using the basal area and the circumference of the stump respectively.

Herrero et al. (2014), when explaining the differences between stands planted in scrub-land, used dummy variables to improve the models for estimating total aboveground biomass in *E. globulus*. Pallardy et al., (2003) studied the clonal variable for poplars using dummy variables to differentiate clones, finding significant differences (<0.05) in the regression parameters, improving the fit of the model.

Conclusions

The number and type of regrowth decreased significantly after 31 months of growth for all species evaluated, the density of 15,000 trees per hectare must have negative effect or the lowest number of proventitious sprouts. The diameter at root collar height, the average height of the two main new shoots and the total number of new sprouts, are highly correlated in the estimation of total aboveground biomass and of its components (stem, branches and leaves). By precluding the need to measure each new shoot as an individual stem and the need to implement pruning practices for each trunk/stump, it was possible to attain good estimations for aboveground biomass in *A. dealbata*, *E. denticulata* and *E. globulus,* which are used as dendroenergetic crops starting from new sprouts. The allometric model showed a lesser fit in its goodness-of-fit statistics. On the other hand, the specific models per genus were the ones that produced the better statistical fit for estimating total aboveground biomass and by component, and the inclusion of dummy variables helped identify the statistical differences in the parameters of the model for the three evaluation dates.

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