Residual biomass in *Eucalyptus globulus* plantations according to stand quality

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Abstract

Residue from *Eucalyptus globulus* plantations is an important source of bioenergy for use in power generation plants.

In this work, a set of equations was developed to calculate the amount of residual biomass in *Eucalyptus globulus* plantations depending on their productivity. The volume of wood underbark was obtained from 321 stands. The stands were divided into 8 categories depending on their productivity (underbark volume of stem wood per hectare and year).

For each component of the residues (leaves, branches and bark), Biomass Expansion Factors (BEFs) were determined using eight plots of different productivities to enable stem volume to predict residual biomass. The bark was the component with the greatest weight in the residue. Our results revealed significant differences (p < 0.01) between BEFs and productivity. The maximum difference was 0.288 Mg m⁻³ and 0.160 Mg m⁻³ between plots categories 8 (lowest productivity) and 1 (highest productivity), respectively.

The equations for estimating the amount of residual biomass only depended on stand productivity. At 15 years of age, it was estimated that 75 Mg ha⁻¹ and 39 Mg ha⁻¹ of residue wood was produced for stand categories 1 and 8, respectively. Finally, predicted residual biomass was compared with that measured in the plots and were slightly lower than those measured in the plots. Relative errors ranged between 1% and 11% at 15 years of age.

Keywords: Bioenergy; Stand productivity; Forestry logging residues; Biomass Expansion Factors; Biomass equations;

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1. Introduction

The expected decrease in fossil energy resources and their impact on the environment has motivated the development of bioenergy as a substitute for fossil fuels.

Forests are considered an energy source as well as carbon sinks. Accumulation of carbon in trees is proportional to their growth rate, so the rate of carbon fixation is increased in fast-growing forest species [1]. Currently, Spain releases 33 Gt of CO_2 into the atmosphere. Of this amount, 26 Gt are derived from the combustion of fossil products, and the remaining is caused by deforestation [2].

The genus *Eucalyptus* is composed of more than 500 species. *Eucalyptus globulus* is the most important species in southern Europe, covering an area of 14,000 km². This species is the most important biomass producer in northern Spain [3] and is managed on a cutting cycle of approximately 15 years [4]. *Eucalyptus globulus* supplies raw material to the pulp and paper industry, which is of great importance to the Spanish economy [5].

Underbark stem wood is the fraction of *Eucalyptus globulus* used for pulp and paper industry with other parts of tree (branches, bark and leaves) being treated as forestry logging residues. This residue can be used as biofuel in power plants to generate electrical and/or thermal energy without fossil carbon dioxide emissions [6]. In addition to mitigating the greenhouse effect since the CO_2 released in the combustion has been previously fixed during tree growth, the removal of this residue from stands adds some environmental advantages, such as reducing the risk of damage by pests and reducing the fire risk by removing much of the potential fuel [7]. As an associated disadvantage, the extraction of nutrients with the elimination of these residues should be mentioned [8, 9]. Knowledge about the amount of residues will help estimate the amount of nutrients extracted per hectare [9].

In the scientific literature, numerous studies have quantified the amount of biomass generated by forest species (Eucalyptus [10-17], Pinus, [18], Populus [19] and Salix viminalis [20]) and herbaceous species (Nauclea diderrichi [21], Chamaecytisus proliferus [22]). In most of these studies, biomass was estimated using empirical equations based on the adjustment of height and diameter data measured in experimental plantations, generally predicting the biomass of individual trees [17-20, 23-27]. In practice, the use of these equations to estimate residual biomass would involve measuring the diameters and the heights of the trees on an industrial scale. To solve this problem, some authors [28, 29] used site index, a measure that quantifies the grow potential of a site based on the dominant height. This process supposes that the dominant height is independent of the environmental, edaphic and silvicultural characteristics. This assumption is true when the growth response is stable and linear [30]. However, in reality, the growth is strongly non-linear due the great variability of the scenarios. For example, it is documented that the relationship between height and diameter varies with altitude, and the trees are thicker and shorter in higher altitudes [31]. This finding implies that different productivities would be obtained for the same value of the site index. Remote sensing techniques have successfully collected data on the volume of stands and other variables, such as the height of the tree crown [30]. However, despite improvements in image processing, the estimates lack accuracy due to topographic and edaphic factors and the multitude of different scenarios that make plantations very complex systems [32, 33]. Improvements in the development of these techniques are necessary to reduce the uncertainty in biomass estimates [34]. Thus, field data are still considered the most suitable way to estimate the amount of biomass [33].

As such, these methods present operational difficulties in estimating the amount of

logging forestry residues on an industrial scale. Therefore, new methods of estimating the amount of forestry residues should be investigated.

Biomass Expansion Factors (BEFs) are multiplying factors that convert volume data into dry biomass data [17, 35-41]. Therefore, errors associated with the estimation of the volume will result in errors in estimation of the amount of biomass. In the present work, this possibility was minimized using the volume data measured in representative plantations by a forest processor. Furthermore, BEFs vary with the species, age, location and characteristics of the stand. Despite this, a simple BEF is normally applied for each species. In the present work, we determined how BEFs vary between stands with different productivity. This method provided better estimations of the amount of residual biomass. A variable called "category" was defined to divide the stands according to their productivity. The stand category was based on the marketable volume and age.

Our objectives were (i) to determine the BEFs of the components of forestry logging residue (leaves, branches and bark) in relation to the productivity of *Eucalyptus globulus* stands and (ii) to develop equations to estimate the residual biomass per hectare from *Eucalyptus globulus* plantations in a way that is useful to the forestry industry.

The analysis method and the conclusions of this proposal are applicable to other countries in which *Eucalyptus globulus labill* is grown, such as Australia, New Zealand, Chile, South Africa, Uruguay, China, Ecuador, Spain, Tunisia, Algeria, Italy, Ethiopia and Portugal [42]. The results of this work will aid in the management of forestry residues in a more efficient and sustainable manner.

2. Material and methods

This section describes the phases that comprise the work.

2.1.- Location

This work was located in Cantabria, northern Spain (latitude 43°28'N, longitude 3°48'W). The area has a maximum average temperature of 25°C in the warmest month and a minimum average temperature of 6°C in the coldest month. The average annual rainfall of 1200-1500 mm is distributed throughout the year, and levels are lower in the summer months. In this region, *Eucalyptus globulus* stands cover 45,000 ha [43] and are located in varied topography with soils mainly classified as Acrisols, Cambisols and Umbrisols [43].

2.2.- Experimental data and division of stands by categories

Data from 321 stands were used to define the categories of productivity. Merchantable volume (volume of wood underbark (m³)), area (ha) and cutting age (year) for each stand were obtained. The marketable volume is the sum of underbark volumes of the harvested trees up to a diameter of 7 cm. Merchantable volume data were collected by a Caterpillar power shovel using a Waratah pickup head. This information was used to create a database that relates merchantable volumes to cutting age (Fig. 1). The stands were heterogeneous plantations formed by seedlings established on marginal agricultural and forest soils of Cantabria. This variability was fundamental since it represents a large number of scenarios. All the factors that influence the production of wood were collected in the productivity category.



Fig. 1. Merchantable stem volume (m³ ha⁻¹) versus cutting age (years) in *Eucalyptus globulus* stands.

Separation of stands into "category" was based on their productivity in terms of underbark wood volume per hectare and year ($m^3ha^{-1}yr^{-1}$). A graphic analysis of the data set (Fig. 1) allowed the stands to be classified into a maximum of eight categories. Fig. 1 shows the linear fit of the stands belonging to each productivity category. Correlation coefficients were significantly different (p <0.05). Residual biomass estimates are improved as the number of productivity categories increases. This number (eight) was obtained under the condition that the productivity means between categories were significantly different (p<0.01).

Table 1 describes the maximum productivity, minimum productivity and the mean productivity defining the cut-off intervals for the eight categories ordered from the highest to the lowest productivity.

Category	Maximum (m ³ ha ⁻¹ yr ⁻¹)	Minimum (m ³ ha ⁻¹ yr ⁻¹)	Mean (m ³ ha ⁻¹ yr ⁻¹)	Number stands
1	31	24	26	19
2	24	22	23	38
3	22	19	20	41
4	19	17	18	69
5	17	15	16	67

Table 1. Cut-off intervals of the eight productivity categories.

6	15	12	13	48	
7	12	10	11	22	
8	10	<10	8	17	

The distribution of stands within categories followed a normal distribution.

2.3.- Conversion of volume data into biomass

Data for BEFs were collected from 8 selected stands, one per productivity category. The mass of each component of the residue and total residual biomass were assessed for each of these stands. For this analysis, a plot of 8 trees was chosen within each stand category at random; thus, there were a total of 8 plots and 64 trees. The plots were chosen to avoid edge effects [44]. In each plot, the diameter of the base (D, cm) and the total height (H, m) were measured for all trees (Table 2). Basal area was calculated from the diameter of the trees. In each plot, the eight trees were felled and separated into components "i" (1 = leaves, 2 = branches, 3 = bark) and stem underbark up to 7 cm top diameter. Once felled, branches, leaves and bark were weighed. Simultaneously, in each plot, four samples were obtained from each component of the laboratory to determine their moisture and the ratio fresh-dry weight. A Sartorius BP121S balance and a Sartorius MA 45 thermogravimetric humidity meter were used for this purpose. The samples are heated at 120°C until the change in their weight is less than 0.1 mg. Dry weight was estimated by difference of moisture in the samples.

Weight of the wood underbark was calculated from the volume of wood underbark of the stem given that its density is 0.571 Mg m⁻³ [45]. The volume of these trees was calculated as a truncated cone, measuring the diameter of the base (D) and height H. All biomass components of trees felled in the plots were expanded to the hectare (Mg ha⁻¹) using the proportion <u>of basal area</u> of felled trees to basal area of the plot. The age of the plots was approximately 15 years. The altitudes of the plots ranged from 100 to 450 metres above sea level.

Stand category	Age (years)	Н	Dm	QMD	BA	NI
		(m)	(cm)	(cm)	(m²ha⁻¹)	IN
1	15.1	21.5	25.1	25.2	57.8	936
2	14.9	20.4	22.1	22.3	42.9	1100
3	15.2	18.9	21.4	21.7	41.9	1136
4	15.3	19.1	19.4	19.3	32.3	1104
5	15.0	18.9	18.1	19.0	31.2	1100
6	14.8	18.0	16.8	18.2	30.6	996
7	15.5	15.8	17.1	15.9	21.7	1015
8	16.1	14.9	12.7	15.0	17.6	1190

Table 2. Stand characteristics of the sampled plots

Note: N is number of trees per ha; D_m (cm) is mean diameter of the trees; H (m) is the height of trees; QMD (cm) is the quadratic mean diameter; BA (m²ha⁻¹) is the basal area.

BEF of the component "i" of the tree "j" (j = 1, ... 8) belonging to plot category "k" (k = 1, ... 8) was calculated using equation 1:

$$\left[(BEF_i)_j \right]_k = \frac{\left[(W_i, j_j)_k \right]_k}{\left[V_j \right]_k}$$
 (Mg m⁻³) (1)

where W_{ijk} (Mg) is aerial biomass of the component "i" in the tree "j" belonging to plot category "k". V_{jk} (m³) is the volume of the stem underbark of the tree "j" of the same plot.

 BEF_{ijk} were plotted against V_{jk} as an independent variable within each plot. This plot helped to explore the relation between the two variables. Subsequently, average BEF_{ik} was chosen for each "i" component as the mean of the 8 trees in each "k" plot. For example, the case of the category 1 plot is shown in Equation 2.

$$\begin{pmatrix} \operatorname{BEF}_{11} \\ \operatorname{BEF}_{21} \\ \operatorname{BEF}_{31} \\ \operatorname{BEF}_{41} \end{pmatrix} = \frac{1}{\mathscr{B}} \cdot \begin{bmatrix} \sum_{j=1}^{\mathscr{B}} (\operatorname{BEF}_{1})_{j} \\ \begin{bmatrix} \sum_{j=1}^{\mathscr{B}} (\operatorname{BEF}_{2})_{j} \\ \\ \begin{bmatrix} \sum_{j=1}^{\mathscr{B}} (\operatorname{BEF}_{3})_{j} \\ \\ \\ \end{bmatrix}_{1}^{\mathscr{B}} (\operatorname{BEF}_{4})_{j} \end{bmatrix}_{1} \end{pmatrix}$$
(2)

For each plot, the average BEF of the residual biomass (BEF_k) was calculated as the sum of the average BEF of the residue components (Equation 3).

$$BEF_{k} = \begin{bmatrix} BEF_{1} \\ BEF_{2} \\ . \\ . \\ BEF_{8} \end{bmatrix} = \begin{bmatrix} BEF_{11} + BEF_{21} + BEF_{31} \\ BEF_{12} + BEF_{22} + BEF_{32} \\ . \\ . \\ BEF_{18} + BEF_{28} + BEF_{38} \end{bmatrix}$$
(3)

2.4.- Equations for estimation of residual biomass

The BEF_k obtained was used to transform the stem volume underbark (Fig. 1) into residual biomass. Residual biomass values were determined based on stand productivity category. The equations related to each stand productivity category (which is straightforward to obtain on an industrial scale) were used to estimate the residual biomass in the plots sampled. The predicted residual biomass was compared to that measured in the plots. This process allowed the goodness of fit of the model to be estimated.

2.5.- Statistical analysis

Analysis of variance (ANOVA) between average BEF_{ik} and plot category was performed to assess significant differences. The normality of the data was tested by Shapiro-Wilks. Then, post hoc tests (Tukey's test) were performed to identify which categories were significantly different. To verify if the average BEF_k and plot category were significantly different, an Analysis of Variance (ANOVA) was performed. Subsequently, post hoc tests were performed to identify which categories were different (Tukey's test, p <0.001). After converting the merchantable volume data into residual biomass data, these data were adjusted for each category. The adjustment method used was a regression by least squares. The performance model was

evaluated on the basis of the coefficient of determination (R²). Statistical analysis was performed with the package SPSS version 2.1.

3. Results and discussion

Fig. 2 shows BEF values obtained for each component of the eight trees in plot productivity category 1 (BEF_{ij1}) and the line that was fitted to the values. The values were adjusted to a line. The coefficients of determination obtained (R^2) were 0.05, 0.41 and 6 10⁻⁵ for the three components of the residue. This finding implies that the regression line does not provide better results than a simple average. For each residue component, a constant BEF was chosen. This value was calculated as the mean BEF of the eight trees. This finding showed that the BEF for each component is independent of the volume of stem wood underbark since the adjustment line has a very small slope. This fact also the case for the other seven productivity categories (Table 3).



Fig. 2. Biomass Expansion Factors, (leaves, branches and bark) of the trees in plot category 1 (BEF_{ij1}).

		R^2	
	Leaves	Branches	Bark
Cat. 1	0.050	0.176	0.000
Cat. 2	0.217	0.547	0.213
Cat. 3	0.025	0.016	0.002
Cat. 4	0.060	0.041	0.049
Cat. 5	0.253	0.073	0.080
Cat. 6	0.145	0.278	0.058
Cat. 7	0.063	0.036	0.022
Cat. 8	0.019	0.309	0.080

Table 3. Determination coefficients for the eight productivity categories.

Mean BEF of residue components in plots sampled is shown in Table 4, (categories). For all components, ANOVA revealed significant differences in mean BEF_{ik} among productivity category. For all components of the residue, the results revealed that BEF_{ik} increased as the productivity of the site decreased. In all the parcels sampled, the proportion of bark was greater followed by branches and leaves. For example, the proportion of leaves in plot category 1 (BEF₁₁ = 0.039) is almost two-thirds of that of plot category 8 (BEF₁₈ = 0.066). The leaves are the fraction with the highest calorific value followed by branches and bark [46]. From this perspective, it can be deduced that quality of fuel is greater in the stands in which the proportion of leaves is greater. Bark was the component in which the differences were more significant between plots. The bark proportion in plot category 8 (BEF₃₈ = 0.133) was twice that of plot category 1 (BEF₃₁ = 0.062). Bark generates largest amount of ash during the combustion of residue. This feature implies that it contains highest concentration of nutrients [47, 48].

The proportion of bark in residual biomass decreased with productivity (Table 4). The proportion was 46.5% in plot category 8 versus 38.5% in plot category 1. Therefore, it can be deduced that the proportion of nutrients extracted in stands with poorer quality (higher category) is increased by removal of forest residue since the percentage of leaves and bark is greater.

	Leaves	Branches	Bark		
	Mean ± Std. Dev.	Mean ± Std. Dev.	Mean ± Std. Dev.		
Cat. 1	0.039 ± 0.003^{a}	0.060 ± 0.004 ^a	0.062 ± 0.005 ª		
Cat. 2	0.041 ± 0.005 ^{a,b}	0.060 ± 0.008 ^{a,b}	0.073 ± 0.005 b		
Cat. 3	0.041 ± 0.006 ^{a,b,c}	0.062 ± 0.012 ^{a,b,c}	0.080 ± 0.006 ^{b,c}		
Cat. 4	0.047 ± 0.012 ^{a,b,c,d}	0.065 ± 0.011 ^{a,b,c,d}	0.093 ± 0.006 ^d		
Cat. 5	0.047 ± 0.014 ^{a,b,c,d,e}	0.065 ± 0.006 ^{a,b,c,d,e}	0.104 ± 0.009 ^{d,e}		
Cat. 6	0.051 ± 0.010 ^{a,b,c,d,e,f}	$0.072 \pm 0.013^{a,b,c,d,e,f}$	0.122 ± 0.009 ^{e,f}		
Cat. 7	0.059 ± 0.008 d,e,f,g	0.085 ± 0.006 f.g	0.129 ± 0.003 ^{f,g}		
Cat. 8	0.066 ± 0.009 ^{d,e,f,g,h}	0.089 ± 0.010 ^{g,h}	0.133 ± 0.006 ^{f,g,h}		
Results associated with the same letter are not significantly different from each other (Tukey's test, p <0.01).					

Table 4. Mean BEF_{ik} (Mg m⁻³) and standard deviation in plots sampled.

Fig. 3 shows the BEF for total residual biomass, and the mean BEF_k for all productivity categories was 0.21775 Mg m⁻³. ANOVA revealed significant differences (p<0.01) between BEF_k of plots sampled. As expected, the proportion of residues increased as plot category increases. For plot category 1 (the highest productivity stands), BEF₁ was 0.1604 versus 0.2880 for plot category 8 (the lowest productivity stands). The results revealed that BEF_k values vary significantly according to plot category in mature *Eucalyptus globulus* plantations. This finding is consistent with the results of Soares and Tome 2012, [38]. They reported variability in BEF_k with respect to site index and planting density. BEF_k remains strongly stable as age increases [38]. The relationship between BEF_k and site index is illustrated in Table 4 since the categories are a type of site index.



Bars associated with the same letter are not significantly different from each other (Tukey's test, p <0.01).

Fig. 3. Mean BEF of residual biomass in plots sampled (BEF_k).

In young *Eucalyptus* stands, BEFs are strongly variable because large changes occur in the components that make up the tree as stands develop [36, 49]. González et al., 2013 [17] reported BEF variability in young plantations of Eucalyptus nitens with high planting densities. As age increases, growth stabilizes, and the stem fraction increases, which increases tree stability [50]. According to [37, 51-54], the proportion of wood increases with age, while other fractions decreases. The BEF of stem is the density of dry wood. When this component increases, the BEF of the total biomass tends to stabilize, masking changes in the BEFs of the remaining components. Soares and Tome [38], studied the variation between the BEF and Site Index age, dominant height, stem volume with bark and stand density. They reported that BEFs for total aboveground biomass are uniform in stands of Eucalyptus globulus older than 5 years in Portugal for these variables. They reported a BEF_{cte} = 0.7225 Mg m⁻³. Therefore, it is well documented that Eucalyptus spp. BEFs stabilize in adult ages. In this study, we found that BEF_k varied between plots of different productivity categories (Fig. 3). Productivity category can be considered a form of Site Index. On other hand, assuming a BEF_{cte} = 0.21775 Mg m⁻³ for all the productivity categories (Fig. 3), the difference between the BEFs reported by both studies is similar to the density of the wood (0.505 Mg m⁻³). This difference is due to the different definition of the BEFs. While [38] defined the BEF as the relationship between the total biomass and the stem with bark volume. In this work, BEF_k was defined as the relationship between the residual biomass and merchantable volume.

 BEF_k values (Fig. 5) were used to convert the data of merchantable volume (Fig. 1) into total residual biomass values. Fig. 4 presents the amount of residual biomass per hectare in a stand according to its productivity category and cutting age. The data were fitted using linear, polynomial, exponential and logarithmic models within the least squares framework. The linear model provided the best fit in terms of the correlation coefficient (R²). At an average age of 15 years, the variation in the amount of residual biomass between category 8 and category 1 was 53%.





Fig. 4. Amount of residual biomass (Mg ha⁻¹) in *Eucalyptus globulus* stands.

The results (Fig. 3) showed that as the productivity category of the stands decreased, the percentage of residue respect volume of wood underbark (BEF_k) increased. However, this increase was not sufficient to generate more residues per hectare (Fig. 4) due to the increase in volume of wood without bark in the best quality stands.

The equations allow us to estimate the amount of residual biomass at the end of harvest based only on knowledge of the volume of wood underbark and stand age. Both variables are easily accessible by the pulp industry.

Fig. 5 (a) showed residual biomass predicted versus observed in the plots sampled. BEF_k was used to calculate predicted residual biomass. For all categories, the amount of residual biomass predicted is less than that observed. Reasonable agreement was noted between residual biomass estimated and observed in category 1, 3 and 8 plots with errors of 11%, 10% and 8%, respectively. Good agreement was noted between residual biomass estimated and observed in category 2, 4, 5, 6 and 7 plots with errors of 5%, 1%, 3%, 1% and 3%, respectively. The model was able to predict the amount of residual biomass in *Eucalyptus globulus* stands according to its category.

Fig. 5 (b) shows predicted residual biomass versus that observed in each category using the constant BEF=0.2775. Greater differences were noted between predicted and observed results when a constant BEF for residual biomass was used. These differences were greater in the extremes with errors of 21% and 31% for the productivity categories 1 and 8, respectively. This fact showed again the improvement in the estimation of the residual biomass with the use of a separate BEF_k for each category.



Fig. 5. Differences between the amount residual biomass predicted and observed using BEF_k associated with each plot category and constant BEF in plots sampled.

4. Conclusions

The use of forestry logging residues of *Eucalyptus globulus* for bioenergy requires the development of tools that allow its quantification. This quantification should be based on variables that are easily measurable on an industrial scale to facilitate the management of this resource.

Variable "category" was defined as the mean volume of wood underbark that a stand generates per hectare and year. This variable is easily obtained once the harvest is complete. The category allowed the stands to be divided based on their productivity.

Significantly different BEFs were found between plots of different categories for all the components of the residual biomass. The most remarkable difference corresponded to the bark component.

The worse the productivity of the stand, the higher the percentage of waste compared to the volume of stem wood. This finding did not imply that the amount of residual biomass per hectare was greater.

The amount of residual biomass per hectare was significantly different in stands belonging to the different productivity categories.

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