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Importance of root system in total biomass for *Eucalyptus globulus* in northern Spain

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ABSTRACT

Biomass equations have become a vital estimation tool and a prerequisite for studies on forest productivity, nutrient cycling and carbon sequestration.

In this paper a new set of biomass equations were fitted for *Eucalyptus globulus* in Northern Spain. These equations allow us to estimate the total biomass and above- and below-ground fractions from the basal area and the height of the tree. A dummy variable was included in the model to calculate the root fraction of planted versus coppice stands.

A descriptive study of the root system was also carried out to complete the information about this component. Root fraction plays an important role in forest structure, but is often omitted in carbon sequestration estimates due to the difficulties and cost associated with measurement. Our results indicated that root biomass accounted for 15% and 35% of total biomass in planted and coppice stands, respectively, at a shoot age equal to 9 years. We also found that the stand type and plantation age influenced the number of roots per root system, the volume of the root system and root length.

This paper brings to light how coppice stands accumulate significant amounts of carbon in their root systems from the time a plantation is established. Such information makes it possible to orient ecosystem management towards potential for C fixation.

1. Introduction

Forests are considered to be mitigating elements against the predicted rise in atmospheric concentration of carbon dioxide, since trees sequester carbon efficiently [1–3]. Plantations can accumulate carbon at a very high rate, especially those composed of fast-growing tree species. In forest plantations, the capacity to sequester carbon is partially influenced by the forest management regime: the age of rotation, silviculture throughout the rotation, timber destination, the type and desired dimensions of the final products, etc.

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The *Eucalyptus* genus has been used in European forestation since the early 19th century because of its high productivity and plasticity. *Eucalyptus* plantations composed mainly of *Eucalyptus globulus*, with an increasing proportion of the frost-tolerant *Eucalyptus nitens*, cover approximately 14,000 km^2 of southern Europe.

E. globulus is a high-productivity crop in Northern Spain. This fast-growing species is managed according to a relatively simple production system based on its precocious, fast growth and ability to re-sprout after harvest. Most plantations are pure stands with a density of aerial trees between 1100 and 1400 ha^{-1}. Stands are normally harvested in three or four cutting cycles of 14–16 years and managed in a coppice system after the first cutting cycle. These plantations mainly produce raw material for the pulp and paper industries, which are important sectors of Spanish economic activity.

Biomass equations have been established for *Eucalyptus* spp. plantations in different parts of the world such as New Zealand [4], Portugal [5,6], Ethiopia [7] or Madagascar [8]. In Spain, Montero [9] fitted the first biomass equations using diameter at breast height as the unique regressor. Later, Pérez-Cruzado [10] and Ruiz-Peinado [11] fitted a set of equations for *E. globulus* that included the additivity property, with diameter at breast height and tree height as independent variables in some biomass fractions. Unfortunately, these equations are inadequate for coppice stands, where trees can be composed of two or more shoots. Furthermore, they only consider the aerial compartments of trees. Very few studies have developed equations for the root system because excavating root systems is difficult and measurements are tedious and very time-consuming. Some research has been done in Australia [12,13], in the Congo [14], in Ethiopia [7], or in Portugal [15].

Detailed knowledge of root system configurations will facilitate better estimation of below-ground biomass and understanding of the role of the root system in improving soil structure [16], in tree anchoring [17] and in nutrient cycles [18,19]. Diverse factors affect root formation and development from the moment a plantation is established, such as physiological functions, adaptability to environmental stresses, site factors, soil conditions and forest management. Until recently, belowground biomass was generally assessed indirectly using the root:shoot ratio (Wr/Wa), which corresponds to the relative biomass allocation between roots and above-ground fractions [15]. However, root biomass estimations using Wr/Wa ratio are prone to error in re-sprouting forests, especially for the youngest trees.

The objective of the present study was to determine the total biomass of *Eucalyptus globulus* plantations in Northern Spain. Our specific objectives were: (i) to fit a set of biomass equations that accounted for the above- and below-ground fractions and the stand regeneration type (planted or coppice stands) and (ii) to analyze the main characteristics of the root system.

2. Material and methods

2.1. The study area

The study area was located in the Cantabria region of northern Spain (between 43° 10′N-43° 30′N, and 3°10′W-4°34′W), which is classified as a Eurosiberian region. Altitudes in the plantations included in this study ranged from 110 to 317 m above sea level. Mean annual rainfall is 1146 mm (summer precipitation 190 mm) and the mean temperature is 14.5 °C. The mean temperatures for the coldest month [January] and the hottest month [August] are 10 °C and 22.9 °C, respectively. About 200,000 ha or 37.8% of the region is forested and *Eucalyptus* spp. plantations cover around 45,000 ha (21.5% of the total forested area). However, according to the Third Spanish National Forest Inventory [20], potential distribution of the species could be higher because 40.4% of the Cantabrian forestlands are not actually covered by forests. The soil is classified as Acrisols, Cambisols and Umbrisols [21], with some horizons of higher clay content; pH 4.3, 3.3% organic C and 0.22% total N in the upper horizon.

2.2. Data

Data from twelve plantations were used to fit dry biomass equations. In each stand, diameter at breast height (d [cm]), total height (ht [m]) and crown height (hc [m]) were measured for all trees in a 30*30 m square plot. Site quality, age and plot density were varied for maximum representativeness (Table 1).

Half of the plots were marked out in planted stands, which are defined as stands in the first rotation and characterized by the age (in years) since establishment. In planted stands, the trees were the original shoots. The remaining plots were marked out in coppice stands, in a forest structure that consisted of multiple shoots per stump following harvest. The coppice stands were characterized by the age of the coppice shoots [shoots that emerged after harvest], the coppice root age [the age of the root system since establishment] and by the number of cutting cycles [number of harvests carried out since establishment]. Four cutting cycles had transpired in the six plots analyzed.

Table 1 – Stand characteristics of the sampled plots.

	Shoot age (years)	N	dm (cm)	QMD (cm)	BA (m^2 ha^{-1})	Ho (m)
Planted stands	6	1222	11.9	11.2	12.1	14.2
	8	1289	11.4	10.7	11.6	17.7
	4	1322	7.4	6.8	4.8	11.7
	11	922	10.7	13.7	13.6	23.7
	10	1344	12.3	11.9	15.0	18.1
	9	1222	13.0	13.0	16.3	20.1
Coppice stands	7	2256	16.4	8.6	13.1	13.3
	6	1744	11.4	7.7	8.2	10.9
	7	1589	16.9	12.6	19.9	19.3
	9	1678	13.8	10.5	14.6	19.2
	16	1878	23.9	15.3	34.7	27.5
	16	2133	27.1	15.3	39.0	28.9

Note: *N* is the stand aerial shoots density per hectare; dm (cm) is the mean diameter of the shoots; QMD (cm) is the shoot quadratic mean diameter; BA (m^2 ha^{-1}) is the stand basal area; Ho (m) is the shoot dominant height; planted stands are the stands in the first rotation after establishment; coppice stands are harvested stands after rotation; shoot age (years) is the plantation age in planted stands and the shoot age in coppice stands.

In all twelve plantations, the basal area of the tree (BA_{tree}) was calculated from the diameter of the shoots. In the planted stands, the basal area of the tree was equivalent to the basal area of the stem, while in coppice stands, the basal area of the tree comprised the sum of the basal area of the different shoots. In a similar manner, tree height (h_{tree}) was calculated as the height of the stem in planted stands and the mean height of the shoots in coppice stands. Accordingly, in this work trees refer to original shoots in planted stands and all shoots per stump in coppice stands.

A total of forty-nine trees, 25 from planted stands and 24 from coppice stands, were felled to obtain biomass samples from both types of stands. Four trees in each plot were proportionally selected for destructive sampling according to the diameter distribution. The number of shoots per stump also was considered as a criterion for tree selection in coppice stands.

The trees were felled, leaving the smallest possible stump, in autumn of 2010. They were then separated into biomass components and weighed in the field in order to ascertain the fresh weight. Thicker stems were measured every meter and their volume was calculated using the Smalian formulation. The basic density of *Eucalyptus globulus* wood, obtained by Tejedor [22] was applied in order to convert volume into dry mass. The biomass weight per tree was estimated according to the methodology described in Montero [9] and divided into the following biomass components: Ws: stem with bark (commercial volume, up to a top diameter of 7 cm), Wthickb: thick branches (diameter greater than 7 cm), Wmb: medium branches (diameter between 2 and 7 cm), Wthinb: thin branches (diameter smaller than 2 cm), Wl: leaves and Wr: coarse roots. Total biomass (Wt) was defined as the sum of aboveground biomass (Wa) and root biomass (Wr). Aboveground biomass (Wa) was defined as the sum of the aboveground biomass fractions of all live trees (Ws + Wthickb + Wmb + Wthinb + Wl). All biomass components of all live trees (*n*) in the plot were expanded to the hectare (Mg ha^{-1}) using the proportion of basal area of the harvested trees to basal area of the plot.

The root:shoot ratio term, Wr/Wa, was also calculated as total belowground to total aboveground tree biomass. The entire root system was extracted with a backhoe and cleaned with water to obtain the fresh and dry root weight and to measure the morphological variables. The number of roots, mean diameter and mean length of each root system were calculated. In each individual root, the large- and small-end diameters, the midpoint diameter, the length and the orientation were recorded in order to determine the root system volume. Individual root volume (m^3) was calculated by Newton's formula [23] and the total root system volume was considered as the sum of all root pieces. Finally, the maximum length of each root system, as well as the main taproot characteristics were recorded.

2.3. Statistical analysis

First of all, descriptive and graphical analyses were carried out in order to determine the different biomass components and their relationships to age and stand variables. All average values of the different biomass fractions (kg $tree^{-1}$) were calculated at a shoot age equal to 9 years for comparison between planted and coppice stands.

Secondly, to assess the influence of the stand regeneration type a linear mixed model was fitted with two levels: stand type (planted, coppice), the shoot age (the age of the plantation) and the interaction between stand type and age in the different biomass fractions. Again, the mean values of the different fractions (Mg ha^{-1}) were calculated at shoot age equal to 9 years in both stand types.

Thirdly, a system of compatible allometric equations was fitted. The first step consisted of testing 13 biomass models obtained from forestry literature. Each biomass fraction was fitted individually using the SAS 9.1 MODEL procedure [24]. All biomass models included combinations or transformations of the basal area of the tree (BA_{tree}) and height of the tree (h_{tree}) as regressor variables. In the analysis, the different fractions were fitted as unique fractions, though some of them were combined, such as stem with bark fraction and thick branches (Ws + thickb) or the leaves and thin branches fraction (Wl + Wthinb). A dummy variable was used in the belowground component to differentiate between planted and coppice stands, reflecting the number of cutting cycles since the establishment of the plantation (four for coppice stands, zero otherwise). Only seven of the 13 models were tested with the dummy variable.

Comparison of the statistical parameters [the sum of the square of residuals (SSE) and the determination coefficient (R^2)] from the 13 models that were fitted for each fraction or combination of fractions made it possible to discover the best model.

The weighted fitting method used the inverse of the variance of the residuals (σ_i^2) to correct the heteroscedasticity problem [25]. The *k* exponent values were added to the fitting program. After fitting, the models were again subjected to heteroscedasticity tests to verify their correctness.

The best models for each fraction were fitted simultaneously by the seemingly unrelated regressions method (SUR) to guarantee the additivity of the system [24]. The SAS 9.1 MODEL procedure [24] was applied to obtain the SUR estimates, using the parameters obtained in the individual fitting as initializers.

Finally, for a complete study of the root system architecture, a general lineal model was carried out to test if the stand type and plantation age corresponded to any significant differences in the main root system dimensions. The SAS 9.1 GLM procedure [24] was applied to fit the model for a shoot age equal to 9 years, in order to homogenize the data for comparison. To complete this step, the SAS 9.1 REG procedure [24] was used to fit a regression model by stand type that related root system volume and basal area of the tree.

3. Results

The aboveground individual tree biomass ranged from 4.0 kg to 637.3 kg. At shoot age equal to 9 years, the results showed an average aboveground individual tree biomass of 81.3 kg in coppice stands and of 110.8 kg in planted stands. This value was composed of the different individual tree biomass fraction averages [planted stands: Ws + thickb = 70.6 kg,

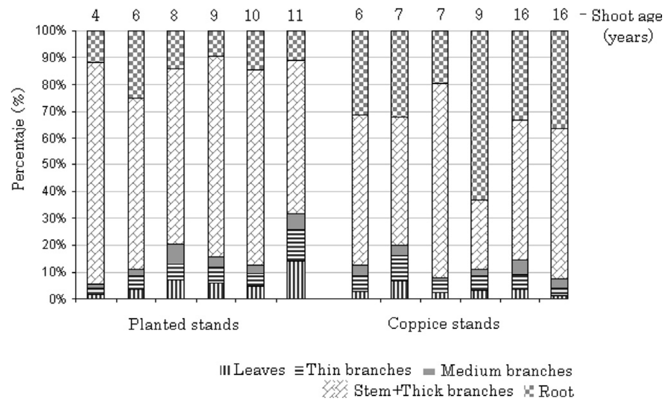

Fig. 1 – Relative percentage of biomass fractions in planted and coppice stands.

Wmb = 2.7, Wthinb = 4.2 and Wl = 3.8 kg; coppice stands: Ws + thickb = 90.8 kg, Wmb = 7.0, Wthinb = 7.8 and Wl = 5.2 kg].

The relative percentage of the biomass fractions in planted and coppiced stands is shown in Fig. 1. So, the biomass values obtained for Wl were similar in planted and in coppice stands, but this was not the case for the other fractions. The crown biomass was almost double in coppice stands (20.1 kg $tree^{-1}$).

Mean individual tree root biomass (Wr) was 14.2 and 60.8 kg in planted and coppice stands, respectively, and ranged from 0.4 kg to 240.8 kg. The total individual tree biomass average, or the sum of Wa and Wr, was 95.5 kg in planted stands and 171.6 kg in coppice stands. The mean value of the Wr/Wa ratio was 0.2 in planted stands and 0.9 in coppice stands, with a minimum value of 0.08 and a maximum of 4.6.

The linear mixed model revealed significant differences in Wmb, Wthinb, Wc, Wr and the Wr/Wa ratio according to the stand type. Higher values were found in coppice than in planted stands (Table 2, Fig. 2).

However, Ws + thickb, Wr, Wa and Wt showed significant differences with regard to the plantation age. As expected, higher Wr values were found in older stands of both types (Fig. 3(a)), and at a similar growth rate. However, the *stand type*age* interaction was significant in the Ws + thickb, Wa and Wt components and the growth rate of the shoot age showed different values in planted and coppice stands. In the youngest plantations, the Wa fraction and the growth rate of the shoot age was higher in planted than in coppice stands (Fig. 3(b and c)). However, at a plantation age of approximately 7 years, the opposite behavior was found in older plantations. A similar pattern was found in Ws + thickb and in Wt. Fig. 3(b and c) which reveals the influence of the aboveground biomass on total biomass.

A system of compatible allometric equations to estimate biomass for tree components was used for *Eucalyptus globulus*. Table 3 gives the results of the fitting procedures for the different models tested and for each biomass component or combination of fractions. Good results were obtained in Model 1 for Ws + Wthickb fractions. Model 3 also showed good statistics in Ws + Wthickb, Wl + Wthinb, Wmb and Wr fractions. Model 3 was selected as the best for the Wmb and Wr fractions, Model 4 was the best option for Wt, Model 10 gave the best results for Ws + Wthickb and Model 11 for Wl + Wthinb.

The results of the final simultaneous fitting and statistics for bias and precision are presented in Table 4. All parameters were significant at the 95% confidence level, and all models included tree basal area and tree height as independent variables. By using the number of cutting cycles we were able to obtain an expression of the root biomass for both planted and coppice stands.

Table 5 shows the main root dimensions by stand type and plantation age. ANOVA revealed that the interaction between stand type and plantation age was not significant. However, significant differences were observed by stand type for the number of roots in each root system, mean length and mean

Table 2 – Dry biomass (Mg ha^{-1}) of the different components by stand type and shoot age since the plantation at shoot age equal to 9 years.

Stand type	n	Dry biomass (Mg ha^{-1})								Wr/Wa
		Ws + thickb	Wmb	Wthinb	Wl	Wc	Wr	Wa	Wt	
Planted	6	52.8	2.7	4.2	3.8	10.5	13.2	63.3	74.3	0.2
Coppice	6	113.6	7.2	7.9	5.4	20.8	60.5	134.5	199.5	0.7
	Factor: Stand type	ns	*	**	ns	*	***	ns	ns	*
	Shoot age	***	ns	ns	ns	ns	**	***	***	ns
	Stand type* Shoot age	*	ns	ns	ns	ns	ns	*	*	ns

Note: Ws + thickb: stem with bark biomass (commercial volume, up to a top diameter of 7 cm) and thick branches biomass (diameter greater than 7 cm); Wmb: medium branches biomass: diameter between 2 and 7 cm; Wthinb: thin branches biomass: diameter smaller than 2 cm; Wl: leaves biomass; Wc: crown biomass: sum of thick, medium, thin branches and leaves biomass; Wr: root biomass; Wa: aboveground biomass; Wt: total biomass; Wr/Wa: root:shoot ratio, which is the ratio between root and aboveground biomass. Significance levels: ***: ($p < 0.001$); **: ($p < 0.01$); *: ($p < 0.05$). ns: not significant.

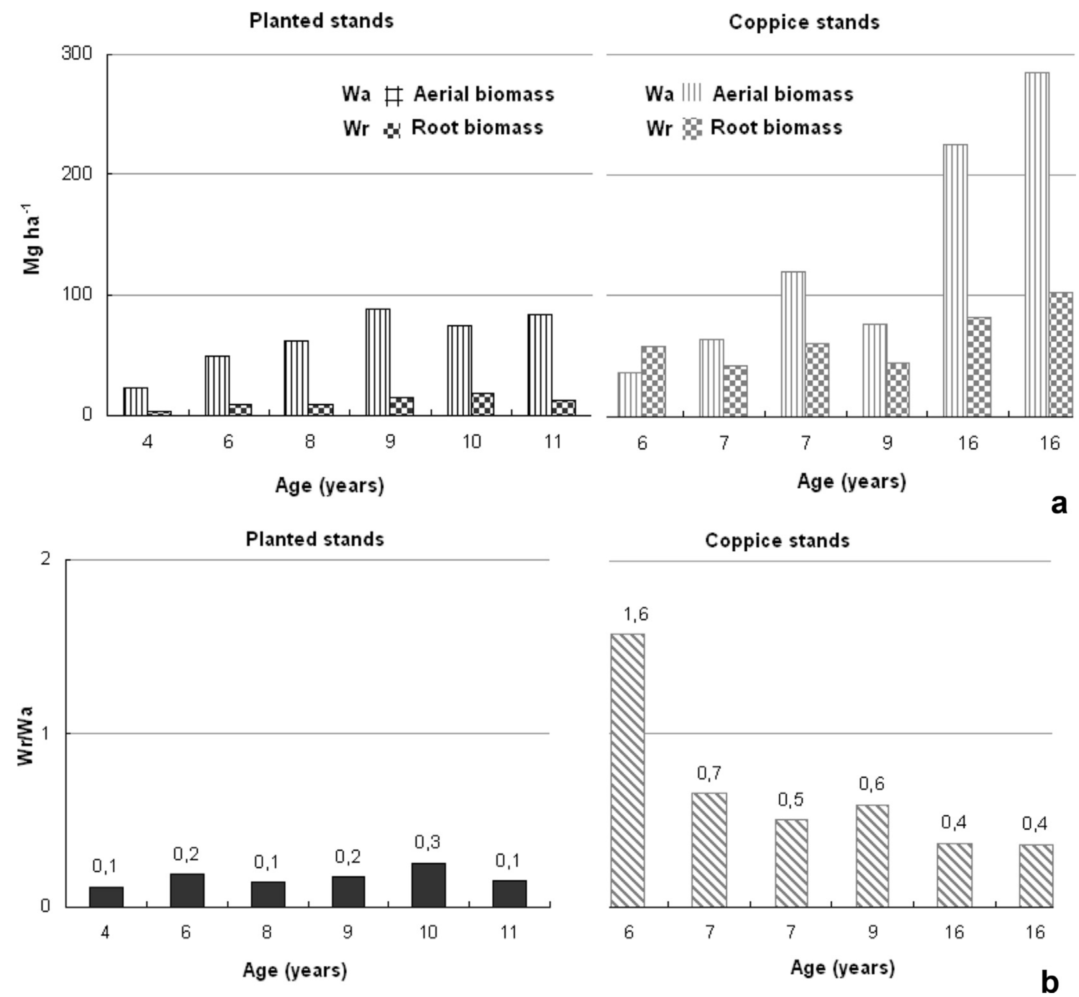

Fig. 2 – Values of Wr, Wa and the Wr/Wa ratio compared to plantation age in planted and coppice stands. Note: *Wr* is the coarse roots biomass fraction; Wa is the aboveground biomass fraction and Wr/Wa is the root:shoot ratio.

root system volume. Higher numbers of roots per root system and higher mean root system volume were found in coppice stands, but the opposite was observed for mean root length. There were also significant differences in number of roots per root system according to the age of the plantation. Fig. 4 shows how the number of roots increased with age in both stand types. Taproots were present in most root systems (96%) and the length of the taproots was similar among stand types (Table 5).

The model that relates the root system volume and the tree basal area gave the following expressions for planted and coppice stands. Under equal basal area conditions, coppice stands showed higher root volume [Eqs. (1) and (2)]:

$$V_{plantedstands} = 0.00098 + 0.00008184 \cdot BA_{tree} \quad R^2 = 074 \quad (1)$$

$$V_{coppicestands} = 0.01289 + 0.00011569 \cdot BA_{tree} R^2 = 0.49 \quad (2)$$

4. Discussion

Previous researchers have arrived at different aboveground individual tree biomass values for this species. Donoso [26] found that Wa ranged from 39.3 to 87.5 kg in young *Eucalyptus globulus* stands. Ruiz-Peinado [11] reported a mean individual tree Wa value of 530 kg for *Eucalyptus globulus* in Southern Spain

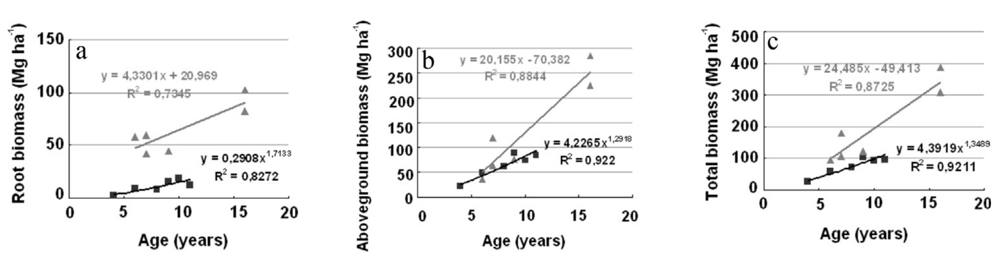

Fig. 3 – a, b, c). Root biomass, aboveground and total biomass (Mg ha^{-1}) and age of the plantation in planted and coppice stands.

Table 3 – Comparison of models in each biomass fraction.

Model	Biomass fraction									
	Ws + Wthickb		Wl + Wthinb		Wmb		Wr		Wt	
	SSE	R^2	SSE	R^2	SSE	R^2	SSE	R^2	SSE	R^2
1	**0.0093**	**0.9839**	0.0026	0.4621	0.0015	0.0753			0.3347	0.8344
2	0.1578	0.7676	0.0054	−0.1066	0.0022	−0.3308			0.9169	0.5461
3	**0.0130**	**0.9771**	**0.0011**	**0.7739**	**0.0010**	**0.3991**	**150599**	**0.6627**	0.1852	0.9064
4	0.0114	0.9795	0.0010	0.7823	0.0010	0.3958	155810	0.6433	**0.1280**	**0.9339**
5	0.0359	0.9368	0.0013	0.7353	0.0011	0.2938	155840	0.6509	0.1794	0.9093
6	0.0650	0.8853	0.0023	0.5211	0.0014	0.1496	174324	0.6095	0.2070	0.8953
7	0.0173	0.9695	0.0023	0.5276	0.0013	0.1910	144203	0.6698	0.3125	0.8420
8	0.0143	0.9742	**0.0015**	**0.6884**	**0.0011**	**0.3480**	193388	0.5668	**0.1322**	**0.9317**
9	0.0093	0.9836	0.0019	0.5985	**0.0011**	**0.3292**	143307	0.6719	0.3244	0.8360
10	**0.0064**	**0.9886**	**0.0015**	**0.6834**	0.0001	0.3539			**0.1386**	**0.9284**
11	**0.0007**	**0.9869**	**0.0007**	**0.8607**	0.0010	0.3604			**0.1308**	**0.9324**
12	0.0153	0.9730	**0.0011**	**0.7646**	0.0011	0.3470			**0.1778**	**0.9101**
13	**0.0075**	**0.9868**	0.0014	0.7059	0.0011	0.3281			0.2453	0.8760

Note: SSE is the sum of the squared error; R^2 is the coefficient of determination; bold type indicates the best models obtained in each biomass fraction. Bold type with shade indicates the selected model.

and Pérez-Cruzado [10] calculated Wa = 237.2 kg as the mean for the same species in Northern Spain.

Our findings corroborate those of previous researchers in plantations of similar age in other parts of the world. In Brazil, Shcumacher [27] reported a mean individual tree Wa value of 39.8 kg in four-year old plantations. Pereira [28] estimated an individual tree Wa of 84.3 kg in a six-year old stand in Portugal. In coppice stands, the values obtained by Pereira [28], Senelwa and Sims [4], Antonio [6] or Zewdie [7] were also within our range. Additionally, in Madagascar, Razakamanarivo [8] obtained similar values for root, leaf and branch biomass fractions, but not for the stem fraction. It is important to acknowledge that comparisons among plantations in different parts of the world can be difficult due to the many differences in climate, soil conditions, species, genetic improvement or forest management.

In prior analyses of the different biomass fractions, Cromer [29] or Cromer and Williams [30] reported biomass proportions of 50–60% for the stem, 11–13% for branches and 15–25% for leaves. Our analysis showed that these values varied according to the stand type. So, our results showed that stem and crown percentages were higher in planted stands, while higher root percentages were observed in coppice stands (Fig. 1).

Our findings for Wa (Mg ha^{-1}) were smaller than those obtained in the Congo [31], Tasmania [32], India [33] and Ethiopia [7]. Much higher values were obtained by Soares and Tomé [15] who reported a maximum Wa value of 157.4 Mg ha^{-1} in fertilized and irrigated plots in a six-year-old plantation and 432 Mg ha^{-1} in 22 year-old Portuguese *Eucalyptus* stands. Higher root biomass values were reported in studies of young *Eucalyptus* plantations in Portugal [34], Madagascar and Cameroon [8], probably due to the differences in system management involving the duration of the plantation, soil fertility and physical constraints.

Our results showed Wr/Wa ratio values from 0.08 to 4.6. Ruiz-Peinado [11] calculated 0.77 for *E. globulus*, which is within our range. Soares and Tomé [15] obtained a smaller value of 0.25 for *E. globulus* in Portugal using a linear equation. Some of our findings were higher than the upper limits reported by Cairns [35] for angiosperm tree types (0.13–0.37), because the values for the youngest coppice stands reflect high root biomass values compared to aboveground biomass. Razakamanarivo [8] reported higher values for coppice stands. In these stands, the Wa fraction is removed in every cutting cycle but the Wr fraction remains. Root biomass continues to increase, along with the capacity to fix carbon and store nutrients for re-sprouting.

In aging coppice stands, the Wr/Wa ratio (Fig. 2(b)) seems to decrease with age, but the statistical analysis did not reveal a significant tendency. Some authors emphasize a decrease in relative root biomass in *Pinus* spp. [36]. or *Picea sitchensis* (Bong) [37], for example, within the first few decades after stand

Table 4 – Final simultaneous biomass equations for *Eucalyptus globulus*.

Model	SSE	MSE	RMSE	R^2	R^2_{adj}
$W_{s+thickb} = 0.000295 \cdot BA_{tree}^2 + 0.028486 \cdot BA_{tree} \cdot h_{tree} - 0.00002 \cdot BA_{tree}^2 \cdot h_{tree}$	896.8	21.1006	4.5935	0.9925	0.9924
$W_{l+thinb} = 0.554369 \cdot BA_{tree}^{1.263759} \cdot h_{tree}^{-1.28465}$	649.6	15.2847	3.9096	0.7864	0.7838
$W_{mb} = 0.000073 \cdot BA_{tree}^2 + 0.145643 \cdot h_{tree}$	1091.6	25.3871	5.0386	0.2570	0.2570
$W_r = 3.404099 * cutting + 0.119168 \cdot BA_{tree} + 0.000088 \cdot cutting \cdot BA_{tree}^2$	22961.8	540.3	23.2439	0.6497	0.6455
$W_t = W_{s+thickb} + W_{l+thinb} + W_{mb} + W_r$	31005.8	805.3	28.3786	0.9172	0.9075

Note: cutting is the dummy variable that shows the number of cutting cycles since the establishment of the plantation [4 in coppice stands; 0 in planted stands]. SSE is the sum of the squared error; MSE is the mean squared error; RMSE is the root mean squared error; R^2 is the coefficient of determination; R^2_{adj} is the adjusted coefficient of determination.

Table 5 – Root dimensions by stand type and shoot age of the plantation at shoot age equal to 9 years.

Stand type		*n* roots/ root	Mean diameter (cm)	Mean length (m)	Mean root system volume (m^3)	Maximum length (m)	Maximum length of taproot (m)	$V_{taproot}$/ V_{total}
Planted		12	3.3	0.67	0.013	1.3	0.99	16.3
Coppice		31	3.2	0.49	0.035	1.15	1.05	12.4
	Factor: Stand type	***	ns	***	**	ns	ns	ns
	Shoot age	*	ns	ns	ns	ns	ns	ns
	Stand type* Shoot age	ns	ns	ns	ns	ns	ns	ns

Note: *n* roots/root is the number of roots per each root system; Significance levels: ***: ($p < 0.001$); **: ($p < 0.01$); *: ($p < 0.05$). ns: not significant.

establishment, followed by a stable and constant ratio. We found that as the age of coppice stands increased the ratio decreased, until approximately half the current rotation length in these forests (14 years). Up to this point, the root system was higher than the aboveground biomass.

It is important to examine the root:shoot ratio because actual growth may depend on the efficiency with which trees acquire and utilize key resources such as light, water, and nutrients. The coordination of growth between the aboveground components (stem, branches, and leaves) and the belowground component is well-documented [38,39]. However, our findings indicate that Wr estimation should be made directly in *Eucalyptus* coppice plantations using biomass equations rather than the Wr/Wa ratio, since this ratio is sensitive to the stand type.

The new biomass models that have been fitted for *Eucalyptus globulus* in this study, offer more accurate results than those obtained by Montero [9], Pérez-Cruzado [10] and Ruiz Peinado [11] in Spain. Our models estimate biomass and carbon stocks with greater precision in planted and coppice *Eucalyptus* plantations, using the basal area and height of the tree as regressors. Inclusion of tree height improves the model by providing information on growth and site conditions [40], as previous researchers have shown [41,42,6,7,11]. The basal area and the height of the tree reflect specific characteristics of the shoots in coppice stands, but the height of the tree represents the mean height of the different shoots. If the height difference between shoots on the same tree is greater than 8 m, we recommend using a weighted average according to the basal area of each shoot instead of the mean tree height value.

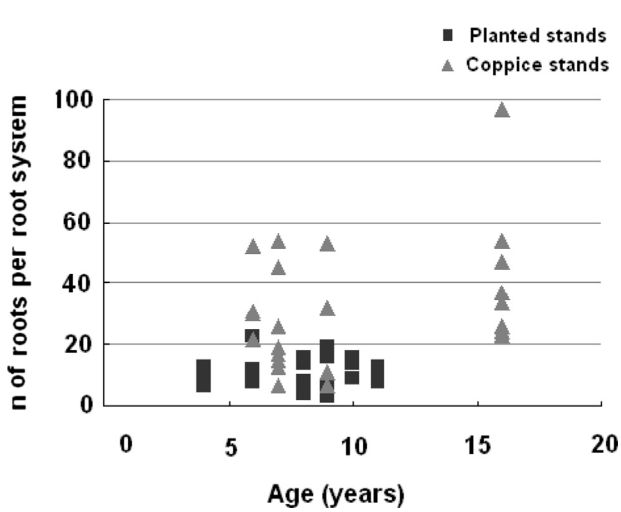

Fig. 4 – Number of roots per root system and age of the plantation in planted and coppice stands.

The inclusion of a dummy variable increased the accuracy of root fraction estimates, along with our understanding of the differences between planted and coppice stands. The model also allowed us to estimate carbon content in the root biomass of *E. globulus* coppice stands at the beginning of the new cutting cycle. This is a significant step forward for biomass estimates involving re-sprouting forests, as it accurately represents the root fraction that remains rotation after rotation (Fig. 5).

Previous researchers have fitted allometric equations for *Eucalyptus* in many parts of the world, such as Senelwa and Sims [4] or Bi [41]. Reed and Tomé [5] and Antonio [6] fitted aboveground biomass equations in Portugal; Zewdie [7] did the same for coppice stands in the central highlands of Ethiopia and Saint-André [14] developed their equations in the Congo. Root systems were either not considered in those studies or (in the last two cases) the equations were fitted without using seemingly unrelated regression (SUR). The efficacy of applying SUR to satisfy the additivity property has been emphasized in other research [43,10,11,44]. The lack of additivity creates logical inconsistency because the predicted values from the biomass equations of the tree components do not add up to the predicted value from the equation for the total tree biomass [45].

Antonio [6] used a dummy variable to fit a set of aboveground biomass equations for coppice and planted stands. However, in that study, coppice stands were dropped from the prediction equations because the different estimates for coppice versus planted stands did not improve the predictive ability of the models. Our equations for root biomass increase the accuracy of the total biomass calculation with respect to previous studies, and thereby improve estimates regarding the carbon sink capacity of *Eucalyptus globulus*.

Diameter, or basal area, and total height are generally recorded in forest inventories and are well correlated to biomass weight. Information about the number of cuttings is also easy to obtain for this type of plantations. Other authors have proposed models that include variables such as crown height [46,6] or sapwood diameters [47]. The variables chosen for this study make it possible to estimate biomass in operational studies.

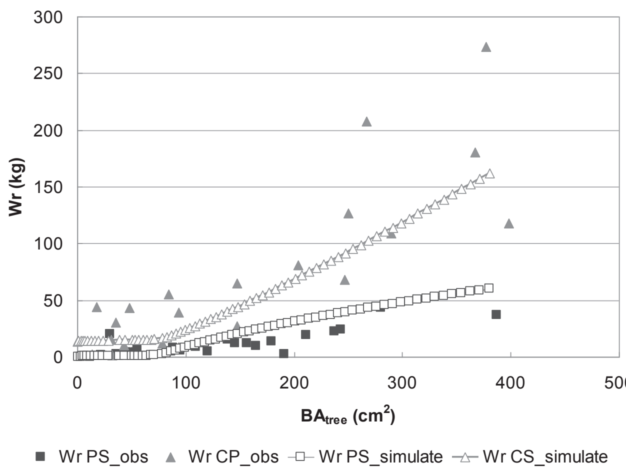

Fig. 5 – Observed and simulated values for the Wr (coarse roots) biomass fraction.

It is common for biomass to increase with stand age in forest ecosystems, though biomass can decline in very old forests [48]. All the models included a negative coefficient of the combined variable square basal area and tree height. This could indicate the asymptotic limit of growth [15] in the models, but this limit was not apparent in our observed values at shoot age equal to 16 years.

The combination of fitted biomass fractions, such as those developed in this study, can be useful in different management options. Normally, stand biomass measurements are linked to productivity; but these equations make it possible to calculate biomass that is either removed or left in forest ecosystems to improve nutrient cycles or C accumulation. In the current bioenergy scenario, biomass data could be highly relevant for developing equation systems that accurately predict fraction biomass for various applications, such as its use for thermal energy and electricity production. Previous authors [49,50] have fitted biomass equations for *E. nitens* to stands intended for biofuel. However, these plantations have different characteristics (density, mean diameter, rotation, management design, etc.) than *E. globulus* plantations intended for pulp and paper in Northwest Spain.

We have developed allometric equations for biomass fractions in planted and coppice stands that can facilitate estimations of belowground carbon sequestration using common forest inventory variables. Quantitative data of root dimensions provided more complete information about this fraction. Our results for root biomass per tree (kg) in planted stands were within the range of the values obtained by previous researchers [51]; and our estimates of the number of roots per root system were within range described by Laclau [52].

Our findings indicated that only a small proportion of belowground biomass production was allocated to the taproot, which implies an important, long and branched root system. Information about the morphology and dimensional configuration of root systems is vital for understanding species adaptation to the site with regard to moisture and nutrient uptake. Root depth and the volume of the root system indicate how much of the soil and which of its components are explored for nutrients and water.

Our study revealed that coppice stands showed greater numbers of roots and root systems with higher volume, but less length than in planted stands. Therefore, length was influenced by factors other than the time since plantation establishment, possibly soil texture or other physical soil characteristics. Previous researchers have observed the influence of soil factors such as clay content, bulk density, lack of aeration [53–55], mechanical impedance and nitrogen supply on the growth of the tree roots [56], soil compaction prior to planting [57] or an abundance of rock/gravel within the potential root zone. We observed a negative though non-significant relation between soil bulk density and root dimensions in planted and coppice stands (Fig. 6).

Our results showed values for root extension and maximum depth that were within the range indicated by previous research [52,55]. Also, we found that length did not increase with the plantation age. Previous researchers [58–60] have reported similar values. In our case, results were influenced by the high resistance of clay-rich soils to penetration. Further research would be necessary to incorporate information about fine root dimensions and distribution in fertilized and non-fertilized plantations, which would generate better understanding of nutrient uptake capacity. Misra [12] suggested that application of N and P in plantations with modest water and nutrient limitations could reduce the relative production of coarse roots and increase the production of aboveground components without significantly affecting total biomass. Root biomass for this species is known to be concentrated in the upper soil profile, because it has been positively related with the accumulation of organic matter, organic Carbon, higher CEC and higher concentrations of the main cations [61,62]. Sainju and Good [61] showed that most of the roots were concentrated in Horizon A.

Our results showed higher numbers of roots with increased age. This was not aligned with the results of other researchers [52], who found smaller numbers of roots in older stands. While some authors have shown increments of different root biomass variables with increased stand age [35], others reported no significant changes in root development with age [17] or demonstrated that root growth had been affected by

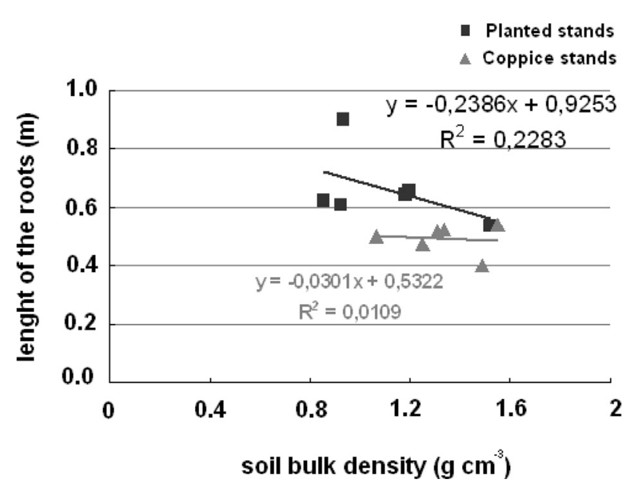

Fig. 6 – Length of roots and bulk density in planted and coppice stands.

soil preparation techniques [56]. This point of disagreement could be due to the dominant effects of site conditions on root morphology [17]. However, it is important to pursue better understanding of optimal root architecture in a stand, as well as soil limitations to acquiring resources and carbon allocation. Information on root morphology also facilitates understanding of tree anchorage [51]. In this particular region, high speed south winds cause significant aboveground damage to plantations. Poorly developed root systems could exacerbate the problem.

Our data also revealed that root systems comprise 15% and 35% of total biomass in planted and coppice *E. globulus* stands, respectively, in northern Spain. In this type of re-sprouting species, as well as in other non-productive but fragile forest ecosystems [44], careful estimation of root biomass is essential to any attempt at quantifying carbon sequestration.

5. Conclusions

Sustainable forest management requires reliable predictive tools for quantifying available biomass and determining the ecological and technological role of forest ecosystems.

In this paper, a new set of fitted biomass equations have been developed for *Eucalyptus globulus* in planted and coppice stands. These equations allow us to estimate the biomass of above- and below-ground fractions with high accuracy and using operational forestry variables, while also taking into account the characteristics of the two stand regeneration types.

Coppice stands were found to have about twice the crown biomass and four times the belowground biomass of planted stands, at a shoot age equal to 9 years. In addition, this complete study of the root configuration revealed that the belowground fraction is composed of a substantial, long and branched root system. Coppice stands presented greater numbers of roots and higher root system volume, but smaller root length. From this, we conclude that root length was influenced by factors other than the time since the establishment of the plantation. Finally, our findings revealed that root biomass (Wr) estimations should be made directly in *Eucalyptus* coppice plantations and with biomass equations rather than the Wr/Wa ratio. This is especially relevant in the youngest stands, where the belowground (Wr) biomass fraction is more important than the aboveground (Wa) fraction.

Our paper draws attention to the accumulation of carbon in the root system of *Eucalyptus globulus*, particularly in coppice stands, where this fraction represents 35% of total biomass and can store carbon for several decades. This feature has not generally been given attention in previous models.

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