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Artigo

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Biomass and carbon content in Galicia (NW Spain) *Eucalyptus globulus* Labill. stands

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Abstract Northwestern Spain is one of the most productive forest areas in Europe, being *Eucalyptus globulus* Labill. the most important species in the area. Stands (pure and mixed) of the species cover more than 400,000 ha, and almost four million cubic metres of timber were produced annually between 2008 and 2012. In this paper we present estimations of total aboveground biomass and the corresponding carbon content in *Eucalyptus globulus* plantations in Galicia, as useful information for further analysis on carbon sequestration balance. We developed several easy-to-use biomass equations, using data collected from cut trees across Galicia, and these were applied to data from the Third (1997) and Fourth (2011) National Forest Inventories in the region. The fitted model with diameter and height as independent variables showed the best estimates (R^2_{Adj} = 0.9965, RMSE = 6.28). Estimations of current (2011) total aboveground biomass was 34.8 Mt and for the carbon was 15.7 Mt.

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Introduction

The *Eucalyptus* genus, which includes almost 600 taxa mostly from Australia (Chippendale, 1988), is one of the most widespread tree species throughout the world because its plantations are highly productive, covering more than 20 million ha (Iglesias-Trabado *et al*., 2009). According to this source, there are about 640,000 ha of *Eucalyptus* stands in Spain, with around 80 species (De La Lama, 1976), mostly stablished as initial trials. *Eucalyptus globulus* Labill. is the most important species in Spain in terms of production. Although *Eucalyptus globulus* stands had purely economic purposes in the area, its growth capacity leads to high annual biomass production and thus a high carbon sequestration rate.

Data from the 4th Spanish National Forest Inventory (SNFI4) (MMAMRM, 2011) indicates that there are 320,774.81 ha of pure *Eucalyptus globulus* stands, 100,245.72 ha of mixed stands with *Pinus pinaster* Ait. and 12,895.30 ha of mixed stands with *Quercus robur* L. in Galicia.

The annual average total harvested volume with bark (m^3_{wb}) in the 1980s was about 500,000 m^3_{wb}, as indicated in the 2nd Spanish National Forest Inventory (SNFI2); this increased to more than 2 million m^3_{wb} in 1997 (SNFI3) and about 3.5 to 4 million m^3_{wb} in 2011 (SNFI4). Reports from the Spanish Wood Confederation (CONFEMADERA) between 2008 and 2012 indicate that harvested volume varied from 3,678,000 m^3_{wb} (in 2008) to 3,095,000 m^3_{wb} (in 2009), 3,574,500 m^3_{wb} (in 2010), 4,145.000 m^3_{wb} (in 2011) and to 3,924.000 m^3_{wb} (in 2012). This implies that *E. globulus* plantations of Galicia provided approximately 50% of the timber harvested in Galicia for all species; almost 75% of the *E. globulus* volume harvested in Spain; and 29.9% of the total volume (for all species) harvested in Spain (Anuario de Estadística Forestal, 2010). In addition, this species is the main source of short pulp fibre (of highest quality) throughout the

European Union, with Spain and Portugal being the main producers of BEKP (*bleached eucalypt kraft pulp*). Also, wood and its derivatives are the second most imported products in the European Union, surpassed only by energy (oil and gas) importations.

In other hand, almost the entire scientific community now accepts the evidence that the climate is changing. This effect has been reported in relation to the trend in annual temperatures in the last 30 years (Trenberth & Josey, 2007), and on a longer timescale in the last century (Jones & Moberg, 2003). The development of adaptation strategies has led to the formulation of new policies based on the reduction of greenhouse gases (GHGs) through the use of renewable energies (solar, wind, biomass, …) and the increase in the forested area, mainly with short rotation forestry species. The high growth potential of *E. globulus* could help to increase the use of renewable energies, aimed to be about 20 % of energy by 2020 according to The National Action Plan for Renewable Energy (PANER 2011-2020).

As this work is only referred to biomass accumulation by the aboveground part of the estimated individual trees by the national inventories, other several studies related to *E. globulus* that have been developed in the region should be considered depending on the focus. For instance, regarding the soils, Merino *et al*. (2003, 2005) studied nutrient flows in young plantations and extraction of nutrients in harvest operations, and Vega-Nieva *et al*. (2013) estimated the fertility rating parameter of a 3PG model. 3PGs models have shown usefulness for operational prediction of forest growth (Landsberg y Waring, 1997), with good results for *E. globulus* in Galicia (Rodríguez-Suárez *et al*., 2010). Pérez-Cruzado *et al*. (2011) developed a density management diagram (DMD) for estimating bioenergy production and carbon sequestration at stand level, and projections of stand variables could be made by using the García and Ruiz (2003) dynamic model.

Thus, the overall objective of this work was to estimate the aboveground biomass and the corresponding carbon sequestered by the *Eucalyptus globulus* stands between the SNFI3 and the SNFI4 in Galicia. The specific objectives were as follows: i) to develop equations for estimating total aboveground biomass in *Eucalyptus globulus* plantations in NW Spain, based on easy-to-obtain independent variables; ii) to compare the fitted models against the existing model (Montero *et al*., 2005) for Galicia; and iii) estimation of carbon content using carbon percentages described by Montero *et al*. (2005) and Brañas *et al*. (2000).

The results should be considered as part of the information for quantifying carbon content, but another information, such as emissions by fires, planting, silvicultural treatments and harvesting, not included in this study, should be added in order to assess actual carbon sequestration.

Materials and methods

Site description

This study was carried out in northwestern Spain, in an inland area located at elevations of 150–600 metres above sea level (m.a.s.l.), with average precipitation of 900–1200 mm and average annual temperature of 12–13º C (Martínez Cortizas and Pérez Alberti, 1999). There are two main bedrock soils: granitic predominating in western Galicia, and schists/shale predominating in eastern Galicia. *E. globulus* plantations are established in both agricultural and forest soils, with predominance of low hills and altitudes less than 500 m.a.s.l.

Data

We used two data sets in this study. The first set (*data1*), for model fitting, consisted of 35 trees from first rotation plantations (no coppiced stumps) included in a network of 128 plots established in Galicia by the Sustainable Forest Management Unit (UXFS). The plots were located across the area of distribution of the species in the region to represent the existing range of ages, stand densities and sites (Figure 1).

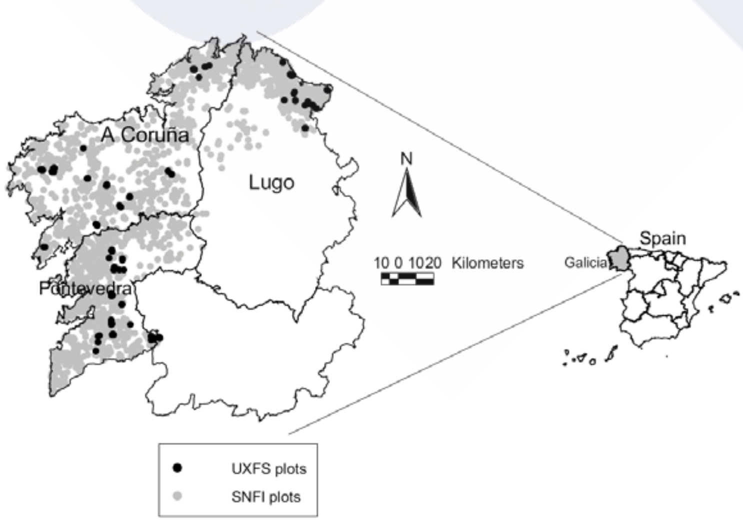

Figure 1.- Location of the measured plots of *Eucalyptus globulus* in Galicia (black) overlayed to 3th SNFI plots (grey)

Table 1 shows a description for *data1*. We collected the following information: diameter at breast height over bark (*d*, cm) and total length of the felled stem (*h*, m). Destructive sampling was carried out separating the stem in one meter logs and the branches in two groups, dead or alive, and by size: thick branches [7-2,5) cm, thin branches [2,5-0,6) cm, twigs d ≤ 0,6 cm and leaves. Fresh weight (kg) for each fraction was taken, and a subsample for dry biomass estimation in each fraction. This subsample consisted of a disk extracted from the bottom of each log and the upper disk of the last log, separating wood and bark, and the 20 % of the fresh weight of each group of branches, as the recommended sampling intensity by Pérez-Cruzado and Rodríguez-Soalleiro (2001). These subsamples were taken to the oven and dried at 105°C to constant weight for dry weight (biomass) estimation.

	Variables							
Statistics	***d (cm)***	***h (m)***	***t (y)***	***W_{tot} (kg)***	***T (y)***	***N (trees ha^{-1})***	***G (m^2 ha^{-1})***	***H_0 (m)***
Mean	12.50	15.10	8.01	77.08	7,6	1340	14,56	17,66
Max	30.85	29.60	17.00	516.60	16	1897	33,10	29,74
Min	2.40	4.00	4.50	2.06	4	820	3,60	7,9
Est. dev	6.49	6.62	3.43	107.03	3,80	330,3	9,06	7,26

d: diameter at breast height (cm); *h*: total tree height (m); *t*: tree age (years); W_{tot}: total aboveground biomass dry weight (kg); *T*: stand age (years); *N*: stand density (trees · ha^{-1}); *G*: basal area (m^2 · ha^{-1}); H_0: dominant height (meters height of the 100 thickest trees · ha^{-1})

Table 1.- Descriptive statistics for the data set used in model fitting

The second data set (*data2*) corresponded to Spanish National Forest Inventories (SNFI) published by the Ministry of Agriculture, Food and Environment (MAGRAMA) in 1997 (SNFI3) and 2011 (SNFI4). This information was obtained from 3867 plots in which *E. globulus* was identified (Figure 1). This data set included the following: area covered for each defined stratum, number of trees in each diameter class in each stratum, and total mean height of all the trees measured in each diameter class. This information was used to estimate biomass and carbon at a regional model and with different models as explained hereafter.

Model fitting

Biomass prediction models are generally based on allometric relationships between biomass and one or more tree variables (Zianis and Mencuccini, 2004), and have been used by several authors for different species (e.g. Madgwick, 1983; Ter-Mikaelian and Korzukhin, 1997; Snowdon *et al*., 2001), and particularly for *Eucalyptus* species (Brañas *et al*., 2000; Bi *et al*., 2000; António *et al.*, 2007; Pérez-Cruzado *et al.*, 2011).

Different authors have indicated that a model based on *d* is enough good (Ter-Mikaelian and Korzukhin, 1997; Verwijst and Telenius, 1999; Brown, 2002), while others have found that models could be easily improved by including the total height, especially in stem biomass, not only for *E. globulus* (Loomis *et al*., 1966; Reed and Tomé, 1998; António *et al*., 2007; Ruiz-Peinado *et al*., 2011). Therefore, two base models were initially evaluated:

$$w = a_0 \cdot d^{a_1} \quad [1]$$

$$w = a_0 \cdot d^2 \cdot h^{a_1} \quad [2]$$

where *w* is the biomass dry weight (kg), *d* is the diameter at breast height (cm), *h* is the total tree height (m), and a_0 and a_1 are the parameters to be estimated.

We estimated the parameters for Eqs. [1] and [2] by the ordinary least squares (OLS) technique, using the *nls* function of R software (R Core Team, 2012).

Although a model for estimating carbon at stand level has been developed (Pérez-Cruzado *et al*., (2011), data from National Inventories contain such information so that individual estimations are possible. Then, an available model for species, developed only with data from *E. globulus* plantations of Huelva, southwest of Spain, was initially considered (Montero *et al*., 2005). Two previous models for biomass developed in Galicia (Brañas *et al*., 2000; Álvarez-González *et al*. 2005) were also considered.

We used the same fitting technique as Montero *et al*. (2005) to fit Eq. [3], based on a linearized model obtained from Eq. [1]. The predictions obtained were modified by applying a correction factor (*CF*) (Eq. [5]) to account for the bias in log-transformed allometric equations (Sprugel, 1983). This correction factor was based on the standard error (*SSE*) of the estimated log value (Eq.[4]). Predictions made by Eq. [6] were therefore compared with those made by Eqs. [1] and [2] and the model by Montero *et al*. (2005), whose parameters are as follows: a_0 = exp(-1,33002), a_1 = 2.19404, *SSE* = 0.15785.

$$\log(w) = \log a_0 + a_1 \cdot \log(d) \quad [3]$$

$$SSE = \sqrt{\frac{\sum(\log(y_i) - \hat{\log}(y_i))^2}{n-2}} \quad [4]$$

$$CF = \exp(SSE^2/2) \quad [5]$$

$$w = CF \cdot a_0 \cdot d^{a_1} \quad [6]$$

We will refer hereafter to each model as follows: *Mod1* for the existing model (Montero *et al*., 2005), where *w* = *f* (*SSE*, *d*); *Mod2* for Eq. [6], where *w* = *f* (*SSE*, *d*); *Mod3* for Eq. [1], where *w* = *f* (*d*); and *Mod4* for Eq. [2], where *w* = *f* (*d*, *h*).

Comparison of the models was based in graphical analysis of the residuals, and four statistical criteria: adjusted coefficient of determination (R^2_{Adj}), root mean square error (RMSE), mean error (BIAS) and Akaike's information criterion (AIC), which we calculated as follows:

$$R^2_{Adj} = 1 - \frac{\sum_{i=1}^{i=n}(Y_i - \hat{Y}_i)^2}{\sum_{i=1}^{i=n}(Y_i - \bar{Y})^2} \cdot \frac{n-1}{n-p} \quad [7]$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{i=n}(Y_i - \hat{Y}_i)^2}{n-p}} \quad [8]$$

$$BIAS = \frac{\sum_{i=1}^{i=n}(Y_i - \hat{Y}_i)}{n} \quad [9]$$

$$AIC = n \cdot Ln\left(\frac{\sum_{i=1}^{i=n}(Y_i - \hat{Y}_i)^2}{n} + 2 \cdot k\right) \quad [10]$$

Biomass and carbon estimation

After fitting the models, they were applied to the SNFI data for each inventory, 3rd and 4th, to estimate the total aboveground biomass in 1997 and 2011 respectively. To estimate the carbon sequestered, different carbon percentages were considered: i) 47.5 % as the percentage of carbon in dry biomass for all the fractions according to Montero *et al*. (2005), to be used with the model of these authors, *Mod1*; ii) the percentages estimated by Brañas *et al*. (2000) for each different biomass fraction (52 %, 46.4 %, 45.3 %, 42.5 % and 45.2 % for leaves, twigs, thin and thick branches, bark and wood respectively) to use with *Mod2*, *Mod3* and *Mod4*.

Root biomass is also an important biomass fraction, however it was not sampled in the trees used in this study and thus root biomass models could not be developed. For this purpose, Montero *et al*. (2005) evaluated root biomass for several stems stablishing a single value of 49 % of the aboveground biomass for this fraction, with the same carbon percentage as mentioned above (47.5 %), and very similar to the 49 % described in Tomé *et al*. (2006).

Results and discussion

Model fitting

Before fitting the models, percentages of each fraction in the sample were obtained: 80.58 % for wood, 9.73 % for bark, 3.52 % for thick branches, 3.47 % for thin branches, 1.45 % for twigs, and 1.22 % for leaves. These values were compared to those described in Montero *et al*. (2005), Álvarez-González *et al*. (2005) and Brañas *et al*. (2000) for *Eucalyptus globulus* (Table 2). All samples had similar values, but for Brañas *et al*. (2000) sample, mainly in the minor fractions.

Further analysis of residuals obtained with Brañas *et al*. (2000) model over *data1* showed high trend to overestimate the biomass in leaves. Also, RMSE values for both available models, Brañas *et al*. (2000) and Álvarez-González *et al*. (2005), larger than desirable, were easily improved when fitting *Mod2*, *Mod3* and *Mod4*. Such improvement could be related to sampling intensity, higher for this study than for previous models. This turn out more important since defoliation disease (*Gonipterus scutellatus* Gyll.) is present in Galician stands, and the natural variability gets influenced.

Data set	Wood + bark	Thick branches	Thin branches + twigs + leaves
Data1	90.3	3.5	6.2
Brañas *et al*. (2000)	82.8	3.3	13.9
Montero *et al*. (2005)	88.1	4.2	7.7
Álvarez-González *et al*. (2005)	89.7	5.4	5.0

Table 2.- Percentages of each fraction in the two data sets used for fitted and available models

All the models fitted in this study provided good results, with R^2_{adj} ranging from 0.96 to 0.99 and RMSE ranging from 6.28 to 22.42 kg (Table 3). The predicted values obtained with *Mod1* were also used to calculate the fit statistics. This model performed very similar to *Mod2,* except for BIAS, for which there was a large difference and high trend to overestimate.

The lowest RMSE value was for *Mod4*, by simply adding total height as independent variable, with similar effect for AIC (Moore, 2010). Crow (1978) and Ketterings *et al*. (2001) also suggested that it is possible to use the same model across different regions provided that height is included in the model and the stage of development is taken into account.

	Parameter estimate			Fit			
Model	a_0	a_1	*SSE*	R^2_{Adj}	RMSE	BIAS	AIC
Mod1	exp(-1.33002)	2.1940	0.1578	0.9478	24.43	-15.09	198.13
Mod2	exp(-2.03092)	2.3396	0.2745	0.9561	22.42	1.06	192.26
Mod3	0.06234	2.6340	-	0.9781	15.81	-0.39	168.67
Mod4	0.02099	0.9628	-	0.9965	6.28	0.76	112.09

Table 3.- Parameter estimates and statistics for the fitted and available models

The three models that included diameter as the only independent variable (i.e. *Mod1*, *Mod2* and *Mod3*) were visually examined (Figure 2). Fitted models (i.e. *Mod2* and *Mod3*) followed similar patterns for small diameters (d < 15 cm), while *Mod1* yielded higher estimates. For trees with d > 15 cm, best estimates were for *Mod1* and *Mod3*, while *Mod2* underestimated the observed values.

Analysis of the residuals against predicted values (Figure 3) revealed very similar structure for models based only on d as independent variable, and not well distributed, whereas errors for *Mod4* were better distributed.

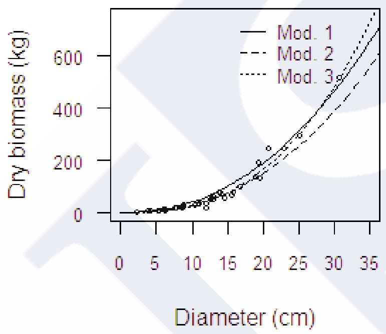

Figure 2.- Predicted values for different diameters obtained with *Mod1*, *Mod2* and *Mod3* overlayed to observed values

Observed values against predicted values (Figure 4) showed that *Mod1* overestimated biomass for all diameters, particularly for the smaller diameters, coming near to the 1:1 line for large trees. *Mod2* underestimated for large diameters, while *Mod3* and *Mod4* showed almost no biased estimates for any of the diameter classes. *Mod4* is then the most recommended for estimating total biomass.

The value of the parameter a_1 in *Mod1* (Montero *et al*., 2005) was lower than the value of the same parameter estimated by *Mod2*. While *data1* belonged to trees in first rotation, the data set used by Montero *et al.* (2005) were older trees belonging from first to third rotation. This seems to be due to the stage of development (António *et al*., 2007), so that the value tends to decrease from younger plantations to older, becoming constant near a value of 2.

This become necessary, since previous analysis showed not convergence for the parameter related to d in Eq. [2] (*Mod4*), set to a value of 2, in the same way as Ruiz-Peinado *et al.* (2011) for conifer species or Álvarez-González *et al.* (2005) for *Eucalyptus*. This value seemed to be the best estimator for a wide range of ages from early stages to ages far beyond the classic rotation age for the species (about 14-15 years).

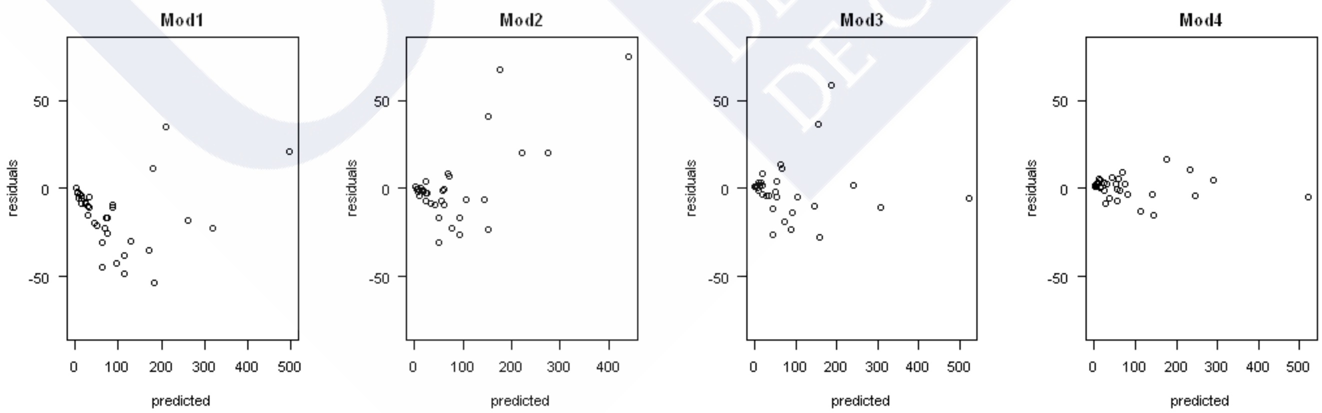

Figure 3.- Residuals against predicted values for the fitted models.

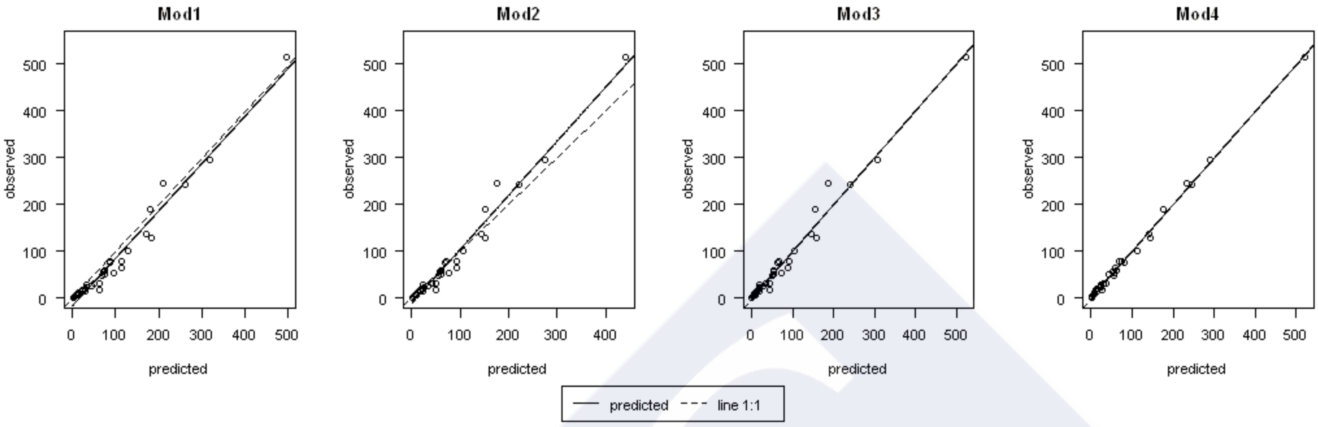

Figure 4.- Observed values against predicted values for *Mod1* (available model) and fitted models *Mod2*, *Mod3* and *Mod4*.In each plot: continuous line for predicted values; dashed line for 1:1

Biomass and carbon estimation

Estimates of total aboveground biomass and the respective carbon content for SNFI3 and SNFI4 using all models are shown in Table 4. Although *Mod4* was considered the best for estimating biomass, *Mod2* provided very similar results, and both lower than those obtained with *Mod1* and *Mod3*.

Mod1 (Montero *et al*., 2005), *Mod2* and *Mod4* showed similar results for large diameters, despite the lack of well balanced data in *data1*. Assuming that model developed by Montero *et al*. (2005) is better for large trees than others fitted in this study, with a maximum diameter sampled of 54 cm, both *Mod2* and *Mod4* appear useful for large trees of diameters > 35 cm. Also, further analysis on total estimated biomass for the SNFI data (Figure 5) revealed that 94.83% of the biomass belonged to trees from 10 to 30 cm. It is logical since mostly the trees belonged to pulp plantations. Thus, the predictions could be considered acceptable with *Mod2* and/or *Mod4* depending on the initial information available. These models applied to SNFI data indicated that biomass increased from 20.4 to 34.88 Mt, and the corresponding carbon content from 9.2 to 15.7 Mt.

Conclusions

The methodology for fitting *Mod2*, previously applied by Montero *et al*. (2005), provided good estimates at the regional level, although better results would be obtained by including total height in the model, as in *Mod4*. As this variable is not always available, both models *Mod2* and *Mod4* are suitable for estimating total aboveground biomass in Galician *Eucalyptus globulus* stands.

Total dry biomass (t)					
SNFI	*Province*	*Mod1*	*Mod2*	*Mod3*	*Mod4*
3	*A Coruña*	*13,070,214*	*10,571,540*	*12,512,240*	*10,089,479*
4	*A Coruña*	*23,957,088*	*19,526,683*	*23,573,216*	*19,175,346*
3	*Lugo*	*7,459,251*	*5,973,364*	*6,958,425*	*5,731,820*
4	*Lugo*	*10,985,662*	*8,834,575*	*10,351,108*	*8,656,136*
3	*Pontevedra*	*5,836,679*	*4,775,032*	*5,835,730*	*4,577,237*
4	*Pontevedra*	*8,590,843*	*7,149,876*	*9,020,323*	*7,052,381*
Total sequestered carbon (t)					
SNFI	*Province*	*Mod1*	*Mod2*	*Mod3*	*Mod4*
3	*A Coruña*	*6,208,352*	*4,761,950*	*5,671,717*	*4,544,806*
4	*A Coruña*	*11,379,617*	*8,795,795*	*10,618,555*	*8,637,535*
3	*Lugo*	*3,543,144*	*2,690,702*	*3,134,422*	*2,581,898*
4	*Lugo*	*5,218,190*	*3,979,534*	*4,662,656*	*3,899,157*
3	*Pontevedra*	*2,772,423*	*2,150,913*	*2,628,705*	*2,061,817*
4	*Pontevedra*	*4,080,651*	*3,220,662*	*4,063,204*	*3,176,745*

Table 4.- Estimates for total aboveground biomass and sequestered carbon (t)

Figure 5.- Total dry biomass (Mt) estimates for 3rd (left) and 4th (right) SNFI data for each diameter class (cm) with all the models

The main drawback of the fitted models is that the data set to develop biomass equations had a maximum diameter of 30.8 cm, and therefore biomass predictions over this size could be uncertain. Therefore, when estimating biomass in bigger trees (over 31 cm) one could use the model by Montero *et al*. (2005) due to these authors included larger trees (with a maximum of 54 cm at breast height).

Regarding the increments in biomass and the corresponding carbon content in the standing trees of *Eucalyptus globulus*, *Mod4* and similarly *Mod2* indicated an increment of 71 % from 1997 to 2011 for the whole region.

As mentioned, carbon in soils and emissions were not included. Therefore, the results here reflected should be taken as a part of the information to asses the carbon sink capacity of eucalypt stands in NW Spain.

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