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Biomass models to estimate carbon stocks for hardwood tree species

R. Ruiz-Peinado[1, 2]*, G. Montero[1, 2], M. del Rio[1, 2]

[1] *Departamento de Selvicultura y Gestión de Sistemas Forestales, INIA-CIFOR, Ctra. A Coruña, km 7.5. 28040. Madrid. Spain*

[2] *Instituto Universitario en Gestión Forestal Sostenible. Universidad de Valladolid-INIA*

Abstract

To estimate forest carbon pools from forest inventories it is necessary to have biomass models or biomass expansion factors. In this study, tree biomass models were developed for the main hardwood forest species in Spain: *Alnus glutinosa*, *Castanea sativa*, *Ceratonia siliqua*, *Eucalyptus globulus*, *Fagus sylvatica*, *Fraxinus angustifolia*, *Olea europaea* var. *sylvestris*, *Populus x euramericana*, *Quercus canariensis*, *Quercus faginea*, *Quercus ilex*, *Quercus pyrenaica* and *Quercus suber*. Different tree biomass components were considered: stem with bark, branches of different sizes, above and belowground biomass. For each species, a system of equations was fitted using seemingly unrelated regression, fulfilling the additivity property between biomass components. Diameter and total height were explored as independent variables. All models included tree diameter whereas for the majority of species, total height was only considered in the stem biomass models and in some of the branch models. The comparison of the new biomass models with previous models fitted separately for each tree component indicated an improvement in the accuracy of the models. A mean reduction of 20% in the root mean square error and a mean increase in the model efficiency of 7% in comparison with recently published models. So, the fitted models allow estimating more accurately the biomass stock in hardwood species from the Spanish National Forest Inventory data.

Key words: aboveground biomass; belowground biomass; additivity; carbon sequestration; hardwood species; biomass models.

Resumen

Ecuaciones para la estimación de biomasa de frondosas en España

Para realizar estimaciones de cantidades de carbono acumulado por los bosques, a partir de datos procedentes de inventarios forestales, es necesario disponer de modelos de estimación de biomasa o de factores de expansión. En este trabajo se han ajustado modelos de estimación de biomasa para las principales especies forestales de frondosas existentes en los bosques españoles: *Alnus glutinosa*, *Castanea sativa*, *Ceratonia siliqua*, *Eucalyptus globulus*, *Fagus sylvatica*, *Fraxinus angustifolia*, *Olea europea* var. sylvestris, *Populus x euramericana*, *Quercus canariensis*, *Quercus faginea*, *Quercus ilex, Quercus pyrenaica* y *Quercus suber*. Se han determinado las siguientes fracciones: fuste con corteza, ramas de diferentes tamaños, parte aérea y parte radical. Para cada especie se ajustó un sistema de ecuaciones utilizando la metodología de mínimos cuadrados generalizados conjuntos, que contempla el cumplimiento de la propiedad aditiva entre fracciones. Como variables independientes se utilizaron el diámetro y la altura total del árbol. El diámetro aparece en todos los modelos, no así la altura, si bien su inclusión resulta en una mejora de las estimaciones en los modelos de biomasa de fuste para la mayoría de las especies y en parte de los modelos de ramas. La comparación con otros modelos desarrollados anteriormente para estas especies y ajustados con otra metodología, indica una mejora en la precisión de los aquí presentados. Existe una mejora media del 20% en términos de la raíz del error medio cuadrático y del 7% en la eficiencia del modelo. Así, mediante el uso de estos modelos ajustados se puede estimar con mayor precisión la biomasa y el carbono acumulado por estas especies de frondosas a partir de datos del Inventario Forestal Nacional de España.

Palabras clave: biomasa aérea; biomasa radical; fijación de carbono; aditividad; frondosas; modelos de estimación de biomasa.

* Corresponding author. ruizpein@inia.es
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Introduction

In recent years, the estimation of forest carbon stocks has gained prominence due to the role of forests in the mitigation of global climate change through carbon storage in biomass and soil. In the Mediterranean area, this role is particularly significant given that non-marketable products and services provided by forests are usually of greater value than their direct productions. Therefore, forest managers require accurate tools for estimating carbon stocks in order to incorporate this aspect into forest management and planning. Carbon estimation is usually carried out using 'indirect' methods which rely on forest inventories because direct estimation approaches are both complex and costly. Hence, biomass models which relate different tree biomass components to dendrometrical variables and biomass expansion factors which relate biomass to stand volume are particularly useful tools in forest biomass estimation (Brown, 2002; Somogyi *et al.*, 2007). Biomass models require tree-level data, which are usually recorded in forest inventories, such as diameter and sometimes height (Teobaldelli *et al.,* 2009). Since biomass expansion factors could depend on site (Wirth *et al*., 2004), age (Lehtonen *et al.,* 2004) or stand timber volume (Fang *et al.,* 2001), if tree-level data is available biomass models are often preferred.

In Spain, stands dominated by hardwood species account for over 46% of the forested area (8.6 million ha), while this percentage rises to 65% (12.2 million ha) if mixed stands are included in the statistic (MARM, 2010). Biomass production has been amply studied in several of these hardwood species such as *Fagus sylvatica* (Santa Regina *et al.*, 1997) given their extensive distribution and importance in wood production. More recently, such studies have been undertaken in plantations of *Eucalyptus* (Merino *et al.*, 2005; Pérez-Cruzado *et al.,* 2011) or hybrids of the genus *Populus* (Sixto-Blanco *et al.*, 2007) due to their importance in bio-energy production. As regards *Quercus* species, *Q. ilex* has also been studied due to its wide distribution in the Mediterranean area (Canadell *et al.*, 1988; Rapp *et al.*, 1999); *Q. pyrenaica* for its firewood production (Carvalho and Parresol, 2003) and *Q. robur* (Balboa-Murias *et al.*, 2006b) because of its ecological importance. However, other *Quercus* species, such as *Q. canariensis*, *Q. faginea* and *Q. suber* have been poorly studied despite their great ecological and economic importance too. A compilation of the literature for biomass estimation in Spain was done in Bravo *et al.* (2011).

Montero *et al.* (2005) developed biomass models for thirty two forest species in Spain in order to quantify the carbon stocks and the potential of Spanish forests as carbon sinks. These are allometric models for the different tree components (stem, branches of different diameters, needles or leaves and root system), which use diameter at the breast height as an independent variable. These models were modified for softwood species by Ruiz-Peinado *et al.* (2011) since they did not fulfill the additivity property (which is highly desirable in this type of model) between tree components (Cunia and Briggs, 1984; Parresol, 1999). Besides diameter, these new equations included total height as an independent variable in order to do more applicability to the models. In this study, we present new biomass models for hardwood species with higher surface distribution and ecological importance in Spain in order to improve the estimations provided by the previous models proposed by Montero *et al.* (2005). As in the case of the models for softwood species (Ruiz-Peinado *et al.,* 2011), we used methods that guarantee the additivity of the tree biomass fractions and we explored the inclusion of tree height as an additional predictor variable.

Material and methods

Study area

The biomass data used for fitting the models were collected in representative regions across the natural distribution areas of these hardwood species in Spain or from areas where these species are cultivated, selecting trees within the pure stands. The location of the sampling sites is presented in Figure 1. Tree data for *Alnus glutinosa* (L.) Gaertn. were collected in the Pyrenean Mountain Range; for *Castanea sativa* Mill. in the Central Mountain Range and Sierra de Ronda; for *Ceratonia siliqua* L. in Sierra de las Nieves; *Eucalyptus globulus* Labill. was sampled in the south of Huelva province; *Fagus sylvatica* L. in the Cantabric Mountain Range and the Pyrenean Mountain Range; *Fraxinus angustifolia* Vahl. in the Pyrenean Mountain Range and in Los Alcornocales Natural Park; *Olea europaea* L. var. *sylvestris* Brot. in the south of Cadiz province; *Populus x euramericana* (Dode) Guinier in the Duero valley in Soria, Segovia and Salamanca provinces (central Spain); *Quercus canariensis* Willd. in Los Alcornocales Natural Park; *Quercus faginea*

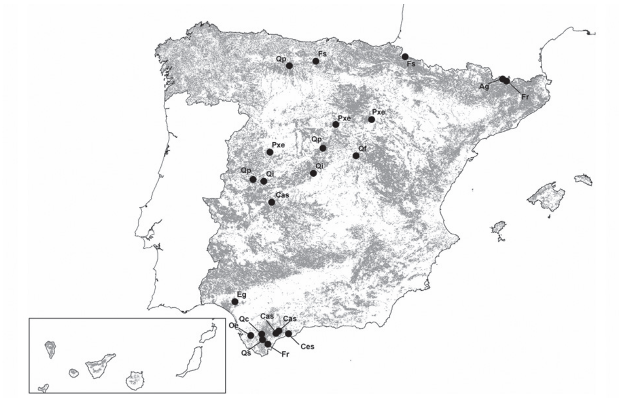

Figure 1. Location of the sample zones in Spain for the studied species. Ag: *Alnus glutinosa*; Cas: *Castanea sativa*; Ces: *Ceratonia siliqua*; Eg: *Eucalyptus globulus*; Fs: *Fagus sylvatica*; Fr: *Fraxinus angustifolia*; Oe: *Olea europaea* var. *sylvestris*; Pxe: *Populus x euramericana*; Qc: *Quercus canariensis*; Qf: *Quercus faginea*; Qi: *Quercus ilex*; Qp: *Quercus pyrenaica*; Qs: *Quercus suber.*

Lamk. in Guadalajara province (Central Spain); *Quercus ilex* L. in Extremadura region and Madrid region; *Quercus pyrenaica* Willd. in Extremadura region, Cantabric Mountain Range and Central Mountain Range; *Quercus suber* L. in Los Alcornocales Natural Park and Sierra de San Pedro.

Data sampling

Individual trees were selected at medium quality sites (stands of medium site index) and those chosen for the destructive sample were taken from among those which displayed normal development and average growing conditions. Diameter at breast height (1.30 m), total height and crown height were measured directly on each tree. Trees were sampled in 5 cm diameter classes, starting at 5 cm up to the maximum diameter found in the area, sampling at least three trees in each diameter classes when it was possible. For *Q. pyrenaica* the sample was completed with available trees from other studies carried out in the CIFOR-INIA. The number of sampled trees varied from a minimum of 16 in the case of *A. glutinosa* to a maximum of 183 trees for *Q. pyrenaica*. A breakdown of the data is shown in Table 1.

Sampled trees were felled, separated into biomass components and weighed in the field in order to obtain the fresh weight. Thicker stems were measured every meter and their volume calculated using the Smalian formulation and then basic density of wood was applied in order to convert volume into dry mass. Methods for estimating the weight of the biomass per fraction of the tree in the field and in the laboratory were the same that those described in Ruiz-Peinado *et al.* (2011). In accordance with the methodology described in Montero *et al.* (1999) we considered the following biomass components: stem with bark (commercial volume, up to a top diameter of 7 cm), thick branches (diameter greater than 7 cm), medium branches (diameter between 2 and 7 cm), thin branches (diameter smaller than 2 cm) and leaves. For some deciduous species (*C. sativa*, *F. sylvatica*, *F. angustifolia* and *Q. pyrenaica*) biomass data were collected in autumn and winter when leaves were not present on the trees so this

Table 1. Minimum, maximum and mean values for diameter, height and biomass weight for the sample trees of the studied species

Species	Diameter (cm)			Height (m)			Aboveground Biomass (kg)				Root Biomass (kg)			
	Min	Max	Mean	Min	Max	Mean	n	Min	Max	Mean	n	Min	Max	Mean
Alnus glutinosa	8.3	47.3	26.8	2.8	16.7	10.6	16	13	625	266	5	13	572	247
*Castanea sativa**	10.7	50.6	27.3	5.8	14.7	9.5	24	72	2,080	689	11	27	1,478	578
Ceratonia siliqua	10.2	42.9	19.0	5.3	12.9	7.3	19	24	599	157	7	33	346	130
Eucalyptus globulus	9.8	54.0	28.6	7.7	25.0	16.8	24	40	1,591	530	–	–	–	–
*Fagus sylvatica**	9.5	74.8	35.1	9.0	30.9	19.8	72	31	3,899	974	14	8	1,134	311
*Fraxinus angustifolia**	7.2	52.2	24.9	2.8	10.0	6.2	26	18	1,278	358	8	34	1,289	466
Olea europaea	10.0	40.5	21.3	4.9	11.0	7.6	17	25	426	171	5	17	222	63
Populus x euramericana	11.4	50.7	28.0	9.6	31.1	19.1	32	28	1,331	380	8	7	309	90
Quercus canariensis	10.0	60.0	29.5	7.5	19.5	13.6	23	22	1,070	404	6	12	452	214
Quercus faginea	9.5	46.5	24.8	4.9	14.7	8.5	24	15	584	212	8	12	479	147
Quercus ilex	7.8	85.9	40.9	3.9	12.5	7.5	43	13	2,506	920	11	101	1,957	570
*Quercus pyrenaica**	5.0	38.2	13.6	4.7	18.1	10.3	183	7	814	100	13	11	789	308
Quercus suber	10.5	83.0	36.5	3.5	14.0	8.7	33	11	2,412	512	11	7	464	160

Min: minimum; Max: maximum; Mean: mean; n: number of samples; *: Aboveground biomass does not include the leaves component.

fraction was excluded from the analysis. Estimation of root biomass was only undertaken on a few trees per species and diameter class due to the complexity and cost of the work involved, so one tree per diameter class were selected to root biomass estimation. The fact that *E. globulus* is managed as a coppice system following the first harvest meant that the estimation of belowground biomass was difficult due to the differing ages of the root systems found on the samples. Therefore, this fraction was excluded for this species.

Thus, the original database from Montero *et al.* (2005) was updated and increased for some species in order to obtain a more widespread sampling along the diameter classes. Nevertheless, some cases the sample could not be completed due to protection status of the species for cut the tree and remove the radical systems.

Statistical analysis

The methodology used to fit the models for tree biomass components was the same as that described by Ruiz-Peinado *et al.* (2011). Fitting was performed in two steps. In a first step, we tested different equations used in the literature and chose the best model according to the goodness of fit statistics: *Mean Residuals* (MRES), *Root Mean Square Error* (RMSE), *Model Efficiency* (MEF) and *Akaike Information Criterion* (AIC). Also we draw the models to evaluate the biological behaviour. A system of equations was then fitted using the best models selected for the different biomass components through seemingly unrelated regressions (SUR) in order to observe the additive property between biomass components (Parresol, 1999; 2001) and weighted regression to avoid heterocedasticity. Belowground biomass models were fitted independently since there were fewer samples for this fraction than for aboveground biomass due to the laborious and time-consuming nature of the work involved. The models were fitted using the SAS/ETS proc MODEL procedure (SAS Institute Inc., 2004). Multicollinearity was also tested using the condition number. Due to problems of multicollinearity it was not possible to fit an individual model for the foliage component of any of the species. Hence, where present, this fraction was included in the thin branch component. Also, when one biomass component presented problems for model fitting, it was included with the next size component.

The models obtained were compared to those presented in Montero *et al*. (2005) through the *RMSE* and *MEF* ratios (Bi *et al.*, 2004) (for more details regarding methodology see Ruiz-Peinado *et al.*, 2011).

Since belowground biomass is closely correlated with aboveground biomass for allometric reasons (Kurz *et al.*, 1996), determining the partitioning of biomass could be useful to apply in other studies or models. In this way, the root:shoot ratios were calculated as the dry mass relationship between the belowground and aboveground biomass of a tree. A Tukey's honest significance test was applied in order to identify differences between the specific mean values ($\alpha = 0.05$; $p < 0.001$).

Results

Maximum aboveground biomass for the sampled hardwood species ranged from 426 kg for *O. europaea* to 3,899 kg for *F. sylvatica* and maximum belowground biomass ranged from 222 kg (*O. europaea*) to 1,957 kg (*Q. ilex)* (Table 1). The models selected through the SUR procedure and statistics for bias and precision (*MRES*, *RMSE* and *MEF*) are shown in Table 2, all parameters being significant at the 95% confidence level.

All the stem biomass models for the studied species included diameter and total height as independent variables, except for *C. siliqua, Q. ilex* and *Q. faginea* which only presented diameter. Diameter was also included in all the models for the other biomass fractions, but the inclusion of total height was restricted to the branch fraction and only for some of the species (Table 2).

The highest model efficiency was obtained by the stem biomass model for each species, exceeding a value of 0.82 in all cases. Even so, most of the models of branches and belowground biomass presented efficiency values of over 0.7. As can be seen from the predicted versus the observed values for aboveground biomass in Figure 2, there is no evidence of bias in the fitted models.

The thick branch component was absent in smaller trees and this fraction only appears when trees reach a certain size. Therefore, most of the models for thick branch biomass presented a restriction based on a threshold diameter, which varied from 12.5 cm for *C. sativa*, *F. angustifolia* and *Q. ilex* to 22.5 cm for *F. sylvatica* and *P. x euramericana*. In other cases, such as for *A. glutinosa*, the sample size was so limited (due to the small number of thick branches) that this com-

Table 2. Biomass models selected from seemingly unrelated regressions and fitting statistics for the hardwood species studied

Species / components	Model	MRES	RMSE	MEF
Alnus glutinosa				
Stem	$W_s = 0.0191 \cdot d^2 \cdot h$	6.01	56.40	0.87
Thick + Medium branches	$W_{b7} + W_{b27} = 0.0512 \cdot d^2$	0.76	22.33	0.78
Thin branches + leaves	$W_{b2+l} = 0.0567 \cdot d \cdot h$	0.35	6.69	0.72
Roots	$W_r = 0.214 \cdot d^2$	11.63	58.89	0.92
Castanea sativa				
Stem	$W_s = 0.0142 \cdot d^2 \cdot h$	12.14	39.29	0.91
Thick branches	If $d \leq 12.5$ cm then $Z = 0$; If $d > 12.5$ cm then $Z = 1$; $W_{b7} = [0.223 \cdot (d - 12.5)^2] \cdot Z$	1.90	27.31	0.92
Medium branches	$W_{b2-7} = 0.230 \cdot d \cdot h$	4.16	36.54	0.63
Thin branches	$W_{b2} = 0.221 \cdot d \cdot h$	4.11	26.48	0.70
Roots	$W_r = 0.0211 \cdot d^{2.804}$	21.36	99.45	0.97
Ceratonia siliqua				
Stem	$W_s = 0.142 \cdot d^{1.974}$	0.43	9.41	0.97
Thick branches	$W_{b7} = 0.104 \cdot d^2$	–0.44	28.91	0.77
Medium branches	$W_{b2-7} = 0.0538 \cdot d^2$	–0.19	11.61	0.75
Thin branches + leaves	$W_{b2+l} = 0.151 \cdot d^2 - 0.00740 \cdot d^2 \cdot h$	0.33	12.88	0.76
Roots	$W_r = 0.335 \cdot d^2$	48.84	10.41	0.97
Eucalyptus globulus				
Stem + Thick branches	$W_{s+b7} = 0.0221 \cdot d^2 \cdot h$	–2.90	69.70	0.97
Medium branches	$W_{b2-7} = 0.154 \cdot d^{1.668}$	–0.83	14.23	0.86
Thin branches + leaves	$W_{b2+l} = 0.180 \cdot (d^2 \cdot h)^{0.587}$	–0.32	17.14	0.83
Fagus sylvatica				
Stem	$W_s = 0.0676 \cdot d^2 + 0.0182 \cdot d^2 \cdot h$	–14.50	157.05	0.94
Thick branches	If $d \leq 22.5$ cm then $Z = 0$; If $d > 22.5$ cm then $Z = 1$; $W_{b7} = [0.830 \cdot (d - 22.5)^2 - 0.0248 \cdot (d - 22.5)^2 \cdot h] \cdot Z$	12.14	100.79	0.65
Medium branches	$W_{b2-7} = 0.0792 \cdot d^2$	2.97	47.83	0.83
Thin branches	$W_{b2} = 0.0930 \cdot d^2 - 0.00226 \cdot d^2 \cdot h$	0.28	24.88	0.80
Roots	$W_r = 0.106 \cdot d^2$	68.21	193.32	0.63
Fraxinus angustifolia				
Stem	$W_s = 0.0296 \cdot d^2 \cdot h$	6.19	37.57	0.93
Thick branches	If $d \leq 12.5$ cm then $Z = 0$; If $d > 12.5$ cm then $Z = 1$; $W_{b7} = [0.231 \cdot (d - 12.5)^2] \cdot Z$	1.91	26.61	0.92
Medium branches	$W_{b2-7} = 0.0925 \cdot d^2$	1.67	15.79	0.94
Thin branches	$W_{b2} = 2.005 \cdot d$	4.81	24.33	0.55
Roots	$W_r = 0.359 \cdot d^2$	23.79	198.70	0.81
Olea europaea var. *sylvestris*				
Stem	$W_s = 0.0114 \cdot d^2 \cdot h$	4.40	18.10	0.82
Thick branches	$W_{b7} = 0.0108 \cdot d^2 \cdot h$	3.02	20.70	0.84
Medium branches	$W_{b2-7} = 1.672 \cdot d$	0.25	17.58	0.54
Thin branches + leaves	$W_{b2+l} = 0.0354 \cdot d^2 + 1.187 \cdot h$	1.37	12.72	0.65
Roots	$W_r = 0.147 \cdot d^2$	3.21	23.81	0.93
Populus x euramericana				
Stem	$W_s = 0.0130 \cdot d^2 \cdot h$	0.72	16.44	0.99
Thick branches	If $d \leq 22.5$ cm then $Z = 0$; If $d > 22.5$ cm then $Z = 1$; $W_{b7} = [0.538 \cdot (d - 22.5)^2 - 0.0130 \cdot (d - 22.5)^2 \cdot h] \cdot Z$	2.96	24.23	0.83
Medium branches	$W_{b2-7} = 0.0385 \cdot d^2$	1.32	19.96	0.77
Thin branches + leaves	$W_{b2+l} = 0.0774 \cdot d^2 - 0.00198 \cdot d^2 \cdot h$	2.79	19.40	0.66
Roots	$W_r = 0.122 \cdot d^2$	1.39	44.80	0.82

Table 2 (cont.). Biomass models selected from seemingly unrelated regressions and fitting statistics for the hardwood species studied

Species / components	Model	MRES	RMSE	MEF
Quercus canariensis				
Stem	$W_s = 0.0126 \cdot d^2 \cdot h$	–2.49	61.86	0.82
Thick branches	$W_{b7} = 0.103 \cdot d^2$	26.72	100.06	0.54
Medium branches + Thin branches + leaves	$W_{b2-7} + W_{b2+1} = 0.167 \cdot d \cdot h$	24.77	35.30	0.63
Roots	$W_r = 0.135 \cdot d^2$	10.69	96.76	0.79
Quercus faginea				
Stem	$W_s = 0.154 \cdot d^2$	1.08	20.98	0.93
Thick branches	$W_{b7} = 0.0861 \cdot d^2$	–7.67	32.84	0.76
Medium branches	$W_{b2-7} = 0.127 \cdot d^2 - 0.00598 \cdot d^2 \cdot h$	–4.21	11.04	0.89
Thin branches + leaves	$W_{b2+1} = 0.0726 \cdot d^2 - 0.00275 \cdot d^2 \cdot h$	–0.09	9.53	0.80
Roots	$W_r = 0.169 \cdot d^2$	–3.20	59.61	0.86
Quercus ilex				
Stem	$W_s = 0.143 \cdot d^2$	1.18	47.18	0.92
Thick branches	If $d \leq 12.5$ cm then $Z = 0$; If $d > 12.5$ cm then $Z = 1$; $W_{b7} = [0.0684 \cdot (d - 12.5)^2 \cdot h] \cdot Z$	48.21	288.70	0.80
Medium branches	$W_{b2-7} = 0.0898 \cdot d^2$	9.87	96.46	0.50
Thin branches + leaves	$W_{b2+1} = 0.0824 \cdot d^2$	8.31	67.35	0.70
Roots	$W_r = 0.254 \cdot d^2$	–15.86	351.04	0.66
Quercus pyrenaica				
Stem + Thick branches	$W_s + W_{b7} = 0.0261 \cdot d^2 \cdot h$	18.21	26.90	0.94
Medium branches	$W_{b2-7} = -0.0260 \cdot d^2 + 0.536 \cdot h + 0.00538 \cdot d^2 \cdot h$	–0.41	8.60	0.78
Thin branches	$W_{b2} = 0.898 \cdot d - 0.445 \cdot h$	–0.23	3.24	0.71
Roots	$W_r = 0.143 \cdot d^2$	–1.21	76.08	0.90
Quercus suber				
Stem	$W_s = 0.00525 \cdot d^2 \cdot h + 0.278 \cdot d \cdot h$	11.60	66.87	0.88
Thick branches	$W_{b7} = 0.0135 \cdot d^2 \cdot h$	38.08	110.76	0.87
Medium branches	$W_{b2-7} = 0.127 \cdot d \cdot h$	6.56	26.47	0.61
Thin branches + leaves	$W_{b2+1} = 0.0463 \cdot d \cdot h$	1.13	8.55	0.68
Roots	$W_r = 0.0829 \cdot d^2$	–0.04	35.39	0.95

W_s: Biomass weight of the stem fraction (kg); W_{b7}: Biomass weight of the thick branches fraction (diameter larger than 7 cm) (kg); W_{b2-7}: Biomass weight of medium branches fraction (diameter between 2 and 7 cm) (kg); W_{b2+1}: Biomass weight of thin branches fraction (diameter smaller than 2 cm) with leaves (kg); W_r: Biomass weight of the belowground fraction (kg); *d*: diameter at breast height (cm); *h*: tree height (m); *MRES*: mean residuals; *RMSE*: root mean square error; *MEF*: model efficiency.

ponent was incorporated into the medium branch fraction. In the case of *E. globulus* and *Q. pyrenaica*, the thick branch component was so limited that it was included as part of the stem fraction since both these fractions, when harvested, are destined for the production of either paper pulp or firewood. The model efficiency for belowground biomass equations reached a value of 0.8 although the figure fell short of 0.7 for *F. sylvatica* and *Q. ilex*.

The *RMSE* and *MEF* ratios calculated to compare the fitted models with those proposed by Montero *et al.* (2005) indicated improved performance for all species using the new models. All the *RMSE* ratios were lower than 1 and the *MEF* ratios higher than 1 for most of the fractions and species (Table 3), with a mean *RMSE* reduction of 20% and a mean *MEF* increase of 7% for aboveground biomass. As regards the different fractions, the greatest improvements in performance were for thick branches and thin branches, although for some species the efficiency of the stem biomass equation increased by more than 25%. With regard to species, the models showing the greatest improvement were those for *A. glutinosa*, *Q. canariensis* and *Q. suber*.

The partitioning of tree biomass into basic fractions as stem, crown (branches of different sizes and foliage when it was present) and belowground biomass is shown in Figure 3. This partitioning is done using the models fitted in this study for a mean tree with a *diameter* of 35 cm and *height* calculated from the sample

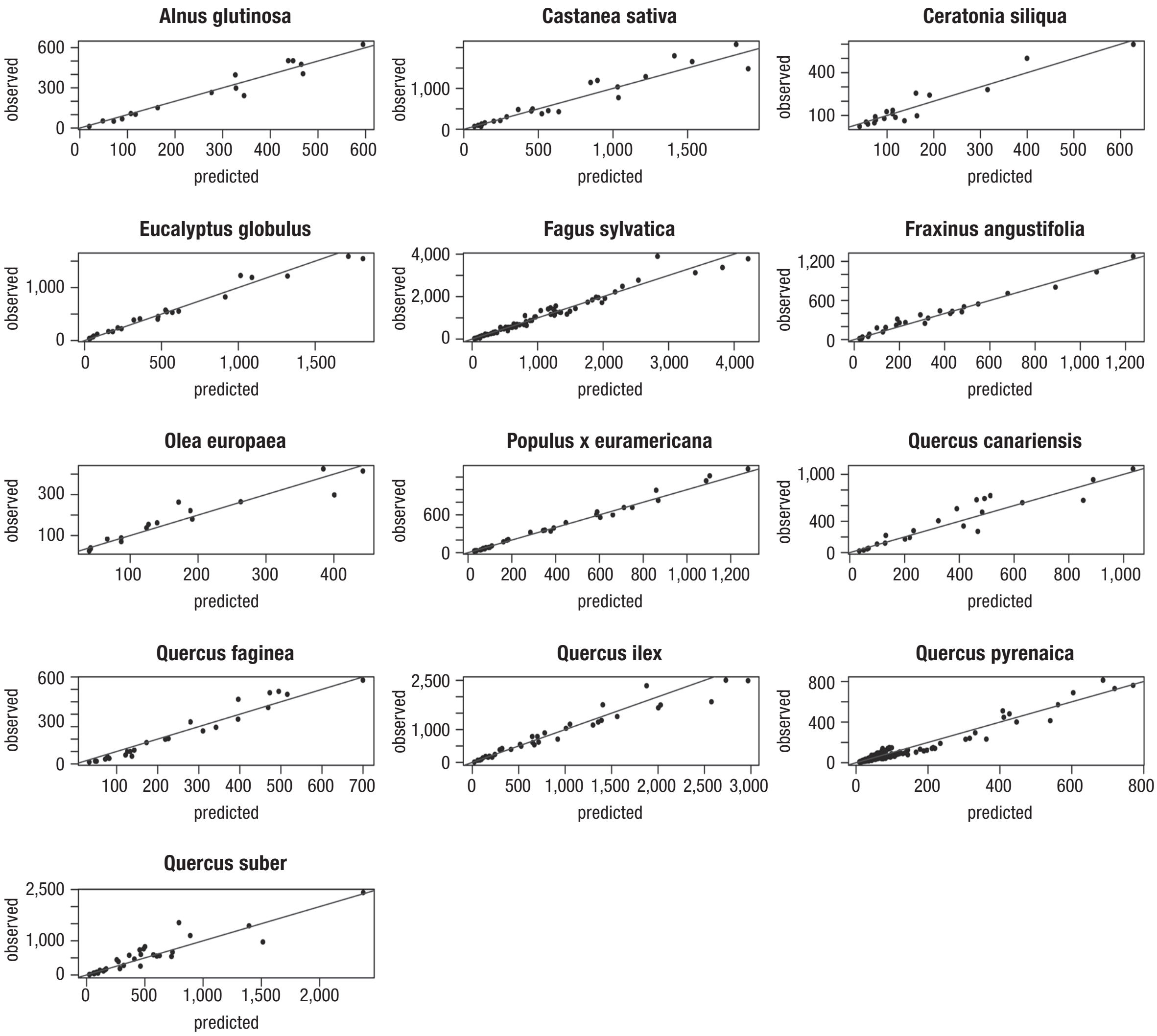

Figure 2. Observed and predicted values for aboveground biomass (kg) of the hardwood studied species. The diagonal line is displaying the 1:1 line.

data. The stem was the biggest fraction in the case of *Q. pyrenaica* (65%, but for this species including the thick branches component), *F. sylvatica* (62%) and *P. x euramericana* (56%) and the smallest fraction for *C. siliqua* (17%). The crown component was the largest biomass fraction for some of these hardwood species as *Q. ilex and Q. suber* with maximum values of 52% and 45% respectively, but also presented minimum values of 13% in the case of *A. glutinosa* and 14% for *Q. pyrenaica*, excluding this case the thick branch component. Root biomass importance varied between species, from nearly half the total biomass to just a seventh. The maximum values for this fraction were 49% and 43% for *C. sativa* and *F. angustifolia* respectively and the minimum values were 15% for *F. sylvatica* and 20% for *Q. suber*.

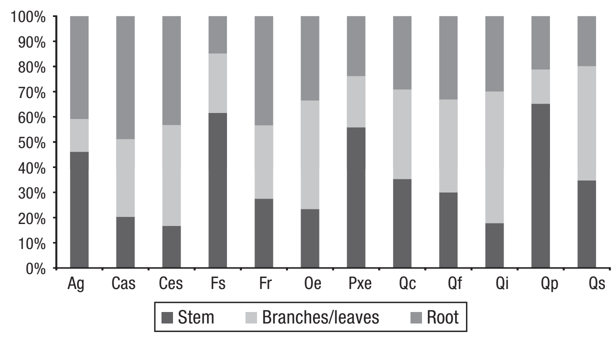

Figure 3. Comparison of biomass partitioning between softwood species for a mean tree with a dbh of 35 cm (mean height to this diameter was calculated from the original data). Ag: *Alnus glutinosa*; Cas: *Castanea sativa*; Ces: *Ceratonia siliqua*; Fs: *Fagus sylvatica*; Fr: *Fraxinus angustifolia*; Oe: *Olea europaea* var. *sylvestris*; Pxe: *Populus x euramericana*; Qc: *Quercus canariensis*; Qf: *Quercus faginea*; Qi: *Quercus ilex*; Qp: *Quercus pyrenaica*; Qs: *Quercus suber*.

Table 3. Root mean square error (*RMSE*) ratio and model efficiency (*MEF*) ratio to compare additive equations fitted in this study and Montero *et al.* (2005) equations (fitted separately for each biomass component using log transformed data)

Species	RMSE Ratio					MEF Ratio				
	W_a	W_s	W_{b7}	W_{b2-7}	W_{b2+l}	W_a	W_s	W_{b7}	W_{b2-7}	W_{b2+l}
Alnus glutinosa	0.86	0.68	0.92		0.72	1.05	1.19	1.05		1.55
Castanea sativa	0.85	0.79	0.90	0.86	0.98	1.05	1.06	1.02	1.26	1.02
Ceratonia siliqua	0.88	0.95	0.69	0.99	0.81	1.04	1.00	1.48	1.01	1.18
Eucalyptus globulus	0.63	0.86		0.94	0.99	1.00	1.01		1.02	1.00
Fagus sylvatica	0.93	0.90	0.86	0.94	0.68	1.01	1.02	1.23	1.03	1.42
Fraxinus angustifolia	0.59	0.79	0.77	0.46	0.66	1.06	1.05	1.07	1.32	1.93
Olea europaea	0.82	0.99	0.60	0.86	0.93	1.07	1.01	1.55	1.45	1.09
Populus x euramericana	0.97	0.27	0.96	0.85	0.81	1.00	1.06	1.02	1.08	1.38
Quercus canariensis	0.65	0.76	0.81	0.74		1.31	1.19	1.66	1.78	
Quercus faginea	0.87	0.88	0.99	0.72	0.76	1.02	1.02	1.01	1.12	1.20
Quercus ilex	0.92	0.82	0.74	0.98	0.99	1.02	1.05	1.10	1.04	1.01
Quercus pyrenaica	0.81	0.86		0.78	0.77	1.04	1.06		1.21	1.39
Quercus suber	0.66	0.64	0.53	0.80	0.76	1.25	1.26	1.59	1.54	1.54

W_a: Aboveground fraction; W_s: Stem fraction; W_{b7}: Thick branches fraction (diameter larger than 7 cm); W_{b2-7}: Medium branches fraction (diameter between 2 and 7 cm); W_{b2+l}: Thin branches fraction (diameter smaller than 2 cm) with leaves (when this component was present).

Mean values for the root:shoot relationships ranged from a maximum of 0.812 for *A. glutinosa* to a minimum of 0.163 for *F. sylvatica*. The mean value considered for the hardwood species studied is 0.466. The Tukey test revealed differences between the means of the root:shoot ratios for the studied species, establishing groups with significantly different values (Table 4). Particularly notable were the high root:shoot ratios found for *A. glutinosa*, *C. siliqua*, *F. angustifolia* and *C. sativa*, with values above 0.75. *O. europea* and *Q. faginea* presented root:shoot ratios around 0.5 and the rest below 0.4.

Table 4. Root:shoot ratios for the studied species, standard error and multiple comparisons.

Species	Root: shoot ratio	Groups *	Std. error
Alnus glutinosa	0.812	a	0.1046
Castanea sativa	0.767	a b c	0.0729
Ceratonia siliqua	0.809	a	0.0944
Eucalyptus globulus	0.771	a b	0.0792
Fagus sylvatica	0.163	e	0.0164
Fraxinus angustifolia	0.504	b c d	0.0995
Olea europaea	0.303	d e	0.0355
Populus x euramericana	0.363	d e	0.0855
Quercus canariensis	0.490	c d	0.0428
Quercus faginea	0.357	d e	0.0497
Quercus ilex	0.323	d e	0.0207
Quercus pyrenaica	0.353	d e	0.0342
Hardwood	0.466		0.0266

* Significant differences are shown by different letters (HSD test; $\alpha = 0.05$; $p < 0.001$).

Discussion

New biomass models fitted in this study for hardwood species improved the previous ones developed by Montero *et al.* (2005) (Table 3), providing more consistent and precise models to estimate biomass and carbon stocks in Spanish forests, to use in nutrient cycling studies (Montero *et al.*, 1999; Blanco *et al.*, 2006), forest planning for bio-energy purposes (López-Rodríguez *et al.*, 2009) or forest management to maximize the carbon sink capacity of forests (Bravo *et al.*, 2008; Cañellas *et al.*, 2008).

The additivity property, which was not satisfied in previously developed equations, was assured through the use of seemingly unrelated regression (SUR) to fit the systems of equations for each species. The application of this fitting method and the inclusion of tree height as a predictor variable resulted in a notable improvement in the performance of the biomass models, particularly for some species, being the *RMSE* mean reduction of a 20% and the *MEF* mean improvement of an 18% (Table 3). Other models for Spanish forest species have also obtained good results using this methodology, such as the previously mentioned models developed by Ruiz-Peinado *et al.* (2011) for softwood species (the accuracy of the estimations up to a 19% improvement for aboveground biomass and 50% for the thick branch component in some species), those of Balboa-Murias *et al.* (2006a; 2006b) for *Pinus pinaster, P. radiata* and *Quercus robur* in the north-west of Spain, or the models for *Eucalyptus globulus* and *E. nitens* developed by Pérez-Cruzado *et al.* (2011).

Diameter and total height were generally recorded in forest inventories and are well correlated with biomass weight, being chosen as models independent variables. The inclusion of height in the models improves the accuracy of biomass estimations (Bi *et al.*, 2004; Joosten *et al.*, 2004) and, hence, the models can be applied in a wider range of stands since height provides information on growth and site conditions (Wirth *et al.,* 2004). Also, other authors have proposed models which also include variables such as tree age (Saint-Andre *et al.*, 2005; Shaiek *et al.*, 2011) or crown height (Loomis *et al.*, 1966; Carvalho and Parresol, 2003) very useful for estimating crown biomass, but we discarded their inclusion because these variables are not usually measured neither in forest inventories nor in the Spanish National Forest Inventory.

Most of the stem models included the combined variable of diameter and height (d^2h), which improved the precision of the estimations (Antonio *et al.*, 2007). Also, this fraction obtained the highest model efficiency using of the combined variable and having the lowest degree of variability. Nevertheless, the inclusion of tree height in the branch models did not always improve the estimations and for this reason was only present in a few cases. Also, in some branch models the coefficients related to height were negative. This may indicate that taller trees have a relatively reduced crown size because they are competing for light (Vanninen and Mäkelä, 2000).

Stem models showed a greater ability for predicting biomass than models for the other components (they explained more than 82% of the observed variation in all cases). Models for branch biomass presented a lower predictive ability, probably due to the high variability observed in this component resulting from differences in stand density and tree competition stage (Návar, 2009). Belowground biomass models only include diameter as independent variable, as stated in other studies (Drexhage and Colin, 2001; Tobin *et al.*, 2007). Since most of the studied hardwood species are resprouters there is a greater degree of variability in belowground biomass, hence the efficiency of the model for this fraction is lower and, in addition, the number of root biomass samples was quite limited for some species, for these reasons more research about belowground biomass is needed to validate it.

Biomass partitioning for the hardwood species showed that only three species present stem values above 50% (Fig. 3), including *Q. pyrenaica* (for which the thick branch component was included). In comparison with the mean values for softwood species reported by Ruiz-Peinado *et al.* (2011), hardwood species allocate a greater proportion of resources to crown and belowground biomass than to the stem. Crown allocation values vary depending on the species, but the mean percentage is greater than for softwood species. Figure 3 also shows that Mediterranean species (*Q. ilex*, *Q. suber*, *O. europaea*, *C. siliqua* and *Q. canariensis*) allocated more biomass in crown (more than 35%) than Eurosiberian species (*A. glutinosa* and *F. sylvatica*), being this pattern also observed in softwood species from *P. halepensis* to *P. uncinata* (Ruiz-Peinado *et al.,* 2011).

The root:shoot ratios found for the hardwood species are in the same range as those reported by other authors. In the case of *F. sylvatica* (a value of 0.163 according to the results of this study), Lebaube *et al.* (2000) found a very similar value (0.15) in France. In the same way, the value found for *Q. ilex* (0.357) is similar to that reported by Canadell and Roda (1991) in Cataluña, north-east Spain (0.41). In other cases, the results vary slightly from those of other studies, such as in the case of poplar for which Federici *et al.* (2008) reports a value of 0.21 in Italy. Mokany *et al*. (2006) presented root:shoot ratios according to vegetation categories, including oak forests where a value of 0.295 was found. Although other authors, such as Cairns *et al.* (1997) and Mokany *et al.* (2006), did not find any differences between groups of species (softwood and hardwood), where Spanish species are concerned the difference between groups is substantial: a mean value of 0.466 for hardwoods (found in this study from 13 species in the Iberian peninsula) and a mean value of 0.265 for softwoods species found by Ruiz-Peinado *et al.* (2011). The higher ratio in hardwoods might be explained by the recent history of broadleaf stands in Spain, where these stands are typically managed as coppice systems to obtain firewood and charcoal. Furthermore, these systems are favored by the recurrence of forest fires. These factors combined with the effect of the Mediterranean climate (Canadell and Roda, 1991) result in deeper, larger root systems which are better adapted for nutrient storage. This occurs in many *Quercus*, *F. angustifolia* and *C. sativa* stands which display high root:shoot ratios.

The different values found and those reported in the literature suggest that root:shoot ratios may not be static relationships, but could depend on tree age (Peichl and Arain, 2007), type of species considered (hardwood-softwood) (Kurz *et al.*, 1996) as reported in this study; or abiotic factors (Cairns *et al.*, 1997) and for these reasons more data for different sites and developed stages would be need to supplement values presented.

Conclusions

The new models presented in this study, which satisfy the additivity property as well as being consistent, provide accurate tools for estimating biomass weight in hardwood species in Spain. The inclusion of total height in some of the models, which reflects growing conditions, improves their accuracy and applicability.

Belowground biomass was found to be one of the largest fractions in many of the hardwood species due to its important role in resource storage. In comparison to softwood species (in which the stem fraction is the largest), hardwood species allocate a greater amount of biomass to the crown and belowground fractions.

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