

# Allometric equations for estimating canopy fuel load and distribution of pole-size maritime pine trees in five Iberian provenances

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**Abstract:** Adequate quantification of canopy fuel load and canopy bulk density is required for assessment of the susceptibility of forest stands to crown fire and evaluation of silvicultural treatments aimed at reducing the risk of crowning. The use of tree biomass equations and vertical profile distributions of crown fuels provide the most accurate estimates of the canopy fuel characteristics. In this study, 100 pole-size maritime pine (*Pinus pinaster* Aiton) trees were destructively sampled in five different sites, covering a wide range of its geographical distribution in the Iberian Peninsula. To estimate crown fuel mass, allometric equations were fitted separately for needles, twigs, and fuel available for crown fire. Models were also fitted to characterize the vertical fuel distributions as a function of tree height. All models were fitted simultaneously to guarantee additivity among tree biomass components, and corrections were also made for heterocedasticity and autocorrelation. Diameter at breast height was the best explanatory variable for all the allometric models. The vertical distribution of crown biomass fractions along tree height depended on the crown size and tree dominance. The system of equations provides a good balance between accurate predictions and low data requirements, allowing quantification of canopy fuel characteristics at stand level.

**Résumé :** La quantification adéquate de la charge de combustibles et de la densité apparente dans le couvert forestier est nécessaire pour évaluer la susceptibilité des peuplements forestiers à un feu de cime et les traitements sylvicoles visant à réduire le risque d'embrasement des cimes. L'utilisation des équations de biomasse des arbres et des profils de répartition verticale des combustibles de cimes procure les estimations les plus précises des caractéristiques des combustibles dans le couvert forestier. Dans cette étude, 100 tiges de pin maritime (*Pinus pinaster* Aiton) au stade du perchis ont été échantillonnées de façon destructive dans cinq stations différentes représentatives d'une vaste partie de l'aire de répartition de l'espèce dans la péninsule ibérique. Pour estimer la masse des combustibles de cimes, des équations allométriques ont été ajustées séparément pour les aiguilles, les rameaux et les combustibles disponibles pour un feu de cime. Des modèles ont également été ajustés pour caractériser la répartition verticale des combustibles en fonction de la hauteur des arbres. Tous les modèles ont été ajustés simultanément pour s'assurer de l'additivité parmi les composantes de la biomasse des arbres et des corrections ont été apportées pour l'hétéroscédasticité et l'autocorrélation. Le diamètre à hauteur de poitrine était la meilleure variable indépendante pour tous les modèles allométriques. La répartition verticale des fractions de biomasse de la cime sur la hauteur d'un arbre dépendait de la dimension de la cime et de la dominance de l'arbre. Le système d'équations constitue un bon équilibre entre la précision des prédictions et la quantité de données nécessaires et permet de quantifier les caractéristiques des combustibles dans le couvert forestier à l'échelle du peuplement. [Traduit par la Rédaction]

## Introduction

Many pine-dominated forests across the Mediterranean area are managed with the aim of maximizing biomass production, which makes them susceptible to high-severity wildfires. Better knowledge of the distribution of forest fuels is imperative for more accurate prediction of forest fire behaviour and for more effective fire management of forest stands. More specifically, information about biomass distribution in the tree canopy fuel layer is essential for characterizing the susceptibility of different forest stands to crown fire (Sando and Wick 1972) and for estimating the behaviour of this highly destructive and resource-consuming type of fire. Adequate characterization of canopy fuel dynamics in relation to different silvicultural regimes would enable development of scientifically based prescriptions for stand structure manipulation aimed at reducing crown fire occurrence (Fernandes and Rigolot 2007). Although different indirect methods of estimating tree biomass variables have been developed, the approach based on destructive sampling and the development of allometric equa-

tions provides the most accurate estimates of site-specific biomass variables (e.g., Brown 1978; Brix 1981; Gillespie et al. 1994; Naidu et al. 1998; Fatemi et al. 2011), and canopy fuel variables related to crown fire (Fulé et al. 2004; Reinhardt et al. 2006). Accurate estimates of canopy fuel variables are not only a basic requirement of the current empirical models of crown fire behaviour (CFIS, FAR-SITE, NEXUS, and Behave), but future physical modelling of crown fire will also require more detailed descriptions of the fuel distribution within tree canopy space. Moreover, other important forest research areas (such as carbon accounting, selective biomass estimation from pruning and thinning treatments, ecological modelling of the light regime within the crown, and physiological modelling of canopy photosynthesis) would also benefit greatly from better knowledge of crown biomass distribution.

Crown bulk density is usually calculated by assuming a uniform vertical distribution of canopy fuel load throughout the canopy depth. The Van Wagner (1977) empirical crown fire propagation model was calibrated considering crown bulk density as the ratio

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**Table 1.** General characteristics of the study plots.

	Coastal Galicia	Inland Galicia	Rodenal	Teleno	Sierra de Guadarrama
Location	42°34'28''N, 8°36'57''W	42°5'43''N, 7°31'9''W	40°11'18''N, 2°8'23''W	42°9'11''N, 6°10'15''W	40°37'58''N, 4°25'10''W
Altitude (m a.s.l.)	200	700	1100	1100	600
Mean slope	12%	20%	14%	6%	8%
Main understorey species	<i>Pteridium aquilinum</i> , <i>Ulex europaeus</i> , and <i>Rubus</i> sp.	<i>Pterospartium tridentatum</i> , and <i>Erica</i> spp.	<i>Cistus laurifolius</i> , <i>Cistus crispus</i> , and <i>Erica australis</i> var. <i>aragonensis</i>	<i>Pterospartium tridentatum</i> , <i>Erica australis</i> , <i>Erica umbellata</i> , and <i>Halimium alyssoides</i>	<i>Cistus ladanifer</i> , <i>Cistus laurifolius</i> , and <i>Pterospartium tridentatum</i>
Mean annual precipitation (mm)	1700	1338	570	650	731
Mean annual temperature (°C)	14.2	9.6	8.8	10.8	10.3
Bedrock	Granitic	Schist	Arenisc	Conglomerates	Granitic
Soil classification	Umbric Regosols	Alumi-umbric regosols	Distric regosols	Distric regosols	Eutric regosols

between crown fuel load and the vertical fuel depth of the canopy layer. However, a more refined approach, taking into account the vertical distribution of canopy fuel load, has been found to be a more accurate way of providing a detailed description of canopy fuels for current and future semiempirical and physical fire behaviour models, such as WFDS and FIRETEC, as load variability within a tree crown alters the timing, magnitude, and dynamics of how fire burns through the crown (Linn et al. 2005; Caraglio et al. 2007; Mell et al. 2009; Parsons et al. 2011; Affleck et al. 2012).

Maritime pine (*Pinus pinaster* Aiton), a characteristic component of Mediterranean forest ecosystems, is also one of the species most prone to crown fire in the region. The wildfire hazard associated with maritime pine stands is of particular concern in areas where high productivity plantations are subject to summer drought. Between 2000 and 2005, approximately 210 000 ha of this species were burned by wildfires in the Iberian Peninsula (MMA 2006; San-Miguel-Ayán et al. 2012). The area burned represents a large part of the forest fire emissions in the Mediterranean area, estimated at about 3.6 Tg CO<sub>2</sub>·year<sup>-1</sup> (van der Werf et al. 2010). In addition, global change scenarios forecast an intensification of summer drought and an increase in temperatures in the Iberian Peninsula, resulting in more frequent and intense wildfires (MMA 2005; Carvalho et al. 2010). Within this framework, adequate characterization of the available fuel in fire-prone species like *P. pinaster* is critical for fuel management and fire behaviour prediction.

Several studies have developed biomass allometric equations for *P. pinaster* (Porté et al. 2000; Balboa-Murias et al. 2006; Shaiek et al. 2011). However, few of these have focused on canopy fuel layer characteristics in relation to crown fire (Fernandes et al. 2002; Madrigal et al. 2006).

Genetic provenance is a factor that potentially influences allometric relationships in conifer species (e.g., Zianis et al. 2011). *Pinus pinaster* exhibits a high degree of genetic variability and is subject to important genotype–environment interactions that favour the existence of adaptations to local ecological conditions, which may influence the allometric relationships (Alfá et al. 1997; Correia et al. 2008). The allometric relationships may also vary depending on growing conditions, including stand density and soil water availability (Vanninen, 2004), cultural treatments (Jiménez et al. 2011), and tree age (Porté et al. 2000), amongst others.

The aim of the present study was to develop a system of allometric equations to estimate available crown fuel load and its vertical distribution (from tree and stand variables) in *P. pinaster* growing in different types of fire-prone landscapes in the Iberian Peninsula. As a consequence of the different provenances and the capacity of the species to adapt to different site conditions, we

hypothesized that it may be necessary to develop specific allometric equations for each site.

## Material and methods

### Study area

Five different *P. pinaster* provenances from the northwestern Spanish coast to central inland Spain were selected for the study: coastal Galicia (province of Pontevedra), inland Galicia (province of Ourense), Rodenal (province of Guadalajara), Teleno (province of León), and Sierra de Guadarrama (province of Ávila). The study focused on representative pole-size stands owing to its high susceptibility to both crown fire initiation and propagation. Moreover, according to the third Spanish National Inventory (MARM 2011a) pole-size trees of this species make up more than 67% of the total trees in the five provenances analyzed, reflecting the important contribution of this type of tree size to the structure of maritime pine stands.

In each provenance area, one stand larger than 500 ha and representative of pole-size stands was randomly selected. Firstly, the Spanish Forest Map (MARM 2011b) was used to locate maritime pine stands larger than 500 ha within each provenance. Then, the database of the third Spanish National Forest Inventory (MARM 2011a) was analyzed to select representative pole-size stands and one of these was randomly selected. The selected sites covered a wide range of biogeographical conditions: the altitude ranged from 200 to 1100 m a.s.l., and the climatic conditions varied from Oceanic (coastal Galicia) to Mediterranean–continental (Rodenal–Guadalajara). The main characteristics of the study sites are summarized in Table 1.

### Tree sampling

For each selected stand, a square grid of 100 m was used to randomly select between 16 and 26 sample points. One tree was subjectively selected close to the sample point to cover the entire range of diameters of the whole stand. In total, 100 *P. pinaster* trees (16 from coastal Galicia, 18 from inland Galicia, 21 from Rodenal, 26 from Teleno, and 19 from Sierra de Guadarrama), were destructively sampled to develop crown biomass equations. Diameter at breast height (DBH); tree height (*h*); crown base height (CBH), defined as the distance from the soil to the point of insertion of the first living branch; and crown width (CW), estimated as the mean of two perpendicular maximum crown widths; were measured for each tree using calipers with 0.1 cm precision and hypsometers with 0.1 m precision. Dominant height (*H*), defined as the mean height of the highest trees (10% of the stand); basal area (*G*); number of trees per hectare (*N*); and quadratic mean diameter (*d<sub>g</sub>*) were obtained from the trees measured in a circular plot of 10 m radius around each selected tree. The DBH, *h*, CBH, and CW

**Table 2.** Descriptive tree and stand characteristics of the *Pinus pinaster* Aiton plots.

Site	DBH (cm)	Height (m)	Age (years)	CBH (m)	CW (m)	BAL (m <sup>2</sup> /ha)	BALMOD	drel	Density (no./ha)	G (m <sup>2</sup> /ha)
<b>Coastal Galicia</b>										
Mean	21.3	15.1	24.4	6.8	3.7	15.0	0.5	1.4	1553	26.2
Max	37.1	20.9	35	11.4	7.0	40.4	1	2.6	3979	46.8
Min	10.6	9.9	11	3.8	1.8	0	0	0.5	354	9.6
<b>Inland Galicia</b>										
Mean	18.4	13.8	33.7	7.6	3.4	20.0	0.6	1.1	1606	34.3
Max	35.0	17.7	57	10.0	5.2	53.3	0.9	1.5	3272	56.5
Min	3.9	6.7	24	2.1	1.5	0	0	0.6	619	13.1
<b>Rodenal</b>										
Mean	18.5	7.4	66.2	3.8	3.0	15.8	0.6	1.3	2143	25.2
Max	34.6	11.9	153	7.1	5.7	44.9	1	2.6	8223	46.5
Min	2.6	2.7	18	0.6	1.0	0	0	0.6	354	11.3
<b>Teleno</b>										
Mean	10.5	5.7	41.1	2.9	1.3	10.6	0.4	1.3	5200	25.9
Max	19.8	8.3	45	3.8	2.8	29.1	1	2.6	6985	52.8
Min	1.7	2.3	29	1.3	0.5	0	0	0.3	2299	11.0
<b>Sierra de Guadarrama</b>										
Mean	13.4	8.6	31.5	4.0	1.9	22.9	0.7	0.9	1824	32.5
Max	22.4	11.4	34	6.0	3.4	42.9	1	1.4	2564	46.0
Min	2.1	3.3	27	1.4	0.8	0	0	0.2	1061	17.0
<b>Total</b>										
Mean	16.3	9.7	40.5	4.8	2.5	16.4	0.6	1.2	2686	28.6
Max	37.1	20.9	153	11.4	7.0	53.3	1	2.6	8223	56.5
Min	1.7	2.3	11	0.6	0.5	0	0	0.2	354	9.6

**Note:** DBH, diameter at breast height; CBH, crown base height (defined as the distance from the soil to the point of insertion of the first living branch); CW, crown width; BAL, basal area of larger trees; BALMOD, ratio between BAL and basal area ( $G$ ); and drel, ratio between DBH and the quadratic mean diameter ( $d_g$ ).

of every tree inside the circular plots were also measured. Crown ratio (CR), defined as the ratio between crown length (CL) and total height, and relative dominance (ReID), defined as the tree height divided by the dominant height of the stand, were also calculated.

The selected trees were felled and sectioned at 1 m height intervals, and the sections were transported to the laboratory. Needles and branches were sorted by diameter fractions (0–0.6 cm, twigs; 0.6–2.5 cm, fine branches; and >2.5 cm, coarse branches) and weighed. Data were obtained from the whole tree, not from the respective fractions. Samples of each fraction and size were oven-dried (105 °C for 48 h until constant mass) to determine the moisture content and for subsequent calculation of biomass on a dry mass basis.

Several methods have been proposed for estimating canopy fuel biomass available for crown fire per tree. For example, Fernandes et al. (2002) used only the foliage fraction; Reinhardt et al. (2006) defined available fuel as foliage, plus live twigs <0.3 cm in diameter, and 0–0.6 cm in diameter dead branchwood classes; and Küçük et al. (2007) considered available canopy fuel load as the needle biomass plus branches <1 cm in diameter. Nevertheless, in the International Crown Fire Modelling Experiment (ICFME), Stocks et al. (2004) found that crown fire consumed 100% of needles, 86% of twigs (<0.5 cm in size), and 62% of fine branches (0.5–3 cm in size). Taking the latter findings into account, we considered available crown fuel load as the sum of needles and twigs (0–0.6 cm), in the same way as Mitsopoulos and Dimitrakopoulos (2007), Keyser and Smith (2010), and Ruiz-González and Álvarez-González (2011). Although other elements such as lichens and bark flakes may contribute significantly to the energy released within the zone of flaming combustion (Agee et al. 2002), these were not included in this or the above-mentioned studies.

Some studies have indicated that crown structure equations, such as aboveground biomass equations, could be improved by including the effect of individual tree competition, because of the strong effect of this factor on crown allometry (e.g., Lintunen and Kaitaniemi 2010). Therefore, three different distance-independent

competition indices were estimated for each tree sampled to be explored as independent variables: BAL (basal area of larger trees), the summarized basal area for all trees greater than the sampled tree; the relative BAL or BALMOD, estimated as the ratio between BAL and the stand basal area ( $G$ ); and the relative diameter (drel), the ratio between the DBH of the sampled tree and the  $d_g$  of the stand. Descriptive tree and stand variables for each site are shown in Table 2.

#### Total biomass equations for each crown fuel fraction

Allometric equations relating the dry mass of each crown biomass fraction (needles and twigs) and available crown fuels (sum of needles and twigs) to tree- and stand-level variables and competition indices, were fitted using the general expression

$$[1] \quad W = \alpha \prod_{i=1}^m X_i^{\beta_i} + \varepsilon$$

where  $W$  represents the dry mass of needles, twigs, or the sum of needles and twigs;  $X_i$  represents a set of  $m$  independent variables (tree- and stand-level variables and competition indices);  $\alpha$  and  $\beta_i$  ( $i = 1, \dots, m$ ) are parameters to be estimated; and  $\varepsilon$  is the error term.

Preliminary analysis of the residuals showed heterocedasticity problems associated with the use of allometric equations, which is a violation of the general assumption of least-squares regression. For this reason, weighted regression was used in which each observation was weighted by the inverse of its variance ( $\sigma_i^2$ ). Although this variance is unknown, it is often assumed that the variance of the error of the  $i$ th individual can be modelled as a power function of a subset of the independent variables, i.e.,  $\sigma_i^2 = (X_i)^k$  (Harvey 1976). The value of the exponential term  $k$  was optimized to provide the most homogeneous Studentized residual plot.

**Table 3.** Allometric biomass equations for needles, twigs, and available crown fine fuels (needles and twigs) obtained by simultaneously fitting the equations system.

Crown fraction	Model	Parameter	Estimation	Std. error	RMSE (kg)	Weighting factor
Needles	$W_n = a_0 \text{DBH}^{b_0} \text{CL}^{b_1}$	$a_0$	0.0117	0.0005	2.7201	$1/\sqrt{(\text{DBH} \times \text{CL})^{2.0805}}$
		$b_0$	1.9356	0.0174		
		$b_1$	0.4836	0.0215		
Twigs	$W_t = a_1 \text{DBH}^{b_2} t^{b_3}$	$a_1$	0.0031	0.0002	1.2214	$1/\sqrt{\text{DBH}^{2.2830}}$
		$b_2$	1.5463	0.0166		
		$b_3$	0.5238	0.0206		
Available crown fine fuels	$W_{n+t} = a_0 \text{DBH}^{b_0} \text{CL}^{b_1} + a_1 \text{DBH}^{b_2} t^{b_3}$				3.3262	$1/\sqrt{(\text{DBH} \times \text{CL})^{2.3636}}$

**Note:** Biomass ( $W$ ) in kg; diameter at breast height (DBH) in cm; crown length (CL) in m; and age ( $t$ ) in years. RMSE, root mean square error. All coefficients were significant at  $p < 0.05$ .

### Influence of site conditions on crown allometry

The hierarchical structure of the data set with sample plots located in different areas requires analysis of the effect of site conditions on the allometric equations.

A log-likelihood ratio test for detecting simultaneous homogeneity among parameters of the total biomass equations was used. The method requires the fitting of full and reduced allometric equations for each biomass fraction. The full equation of each biomass fraction corresponds to different sets of parameters for each site, and it is obtained by including site effects as dummy categorical variables. These variables take a value of 1 if the observation comes from the site and 0 if it comes from another site. To evaluate intersite differences, reduced allometric equations incorporating an additional hypothesis of equal site effects were also fitted. After testing the significance of the parameters, the log-likelihood ratio test was carried out to compare the reduced equations with the full equation including all regional dummies for each biomass fraction. The appropriate test statistic is given by

$$[2] \quad L = [\text{SSE(F)}/\text{SSE(R)}]^{n/2}$$

where  $-2 \ln(L)$  follows a  $\chi^2$  distribution with  $v = df_R - df_F$  degrees of freedom; SSE(F) is the error sum of squares of the full equation; SSE(R) is the error sum of squares of the reduced equation;  $L$  is the likelihood ratio test; and  $df_R$  and  $df_F$  are the degrees of freedom of error of the reduced and full equations, respectively.

If the ratio test reveals that the differences are not significant, the reduced equation can be used instead of the full equation.

### Biomass ratio equations for each crown fuel fraction

The vertical distribution profile of the biomass of each crown fraction was initially established following the method proposed by Alexander et al. (2004). Starting from the crown apex of every tree used for the destructive inventory, the cumulative ratio ( $W_n(h_i)/W_n$ ) between the dry mass of each 1 m section and the total dry mass of the crown fraction was calculated separately. The relative height ( $h_i/h$ ), defined as the ratio of the height of each one meter section to the total height of the tree, was also obtained. The relationship between  $W_n(h_i)/W_n$  and  $h_i/h$  was fitted by the two-parameter Weibull distribution

$$[3] \quad \frac{W_n(h_i)}{W_n} = 1 - \exp \left[ - \left( \frac{h_i/h}{c_0} \right)^{c_1} \right]$$

where  $c_0$  and  $c_1$  are the estimated scale and shape parameters, respectively.

The biomass ratio equations were fitted to data from each individual tree to analyse the effect of tree size, tree competition, and stand density. Linear models were fitted to analyse the dependence of the scale and shape parameters on tree- and (or) stand-

level variables. Selection of the best set of independent variables was based on the "stepwise" approach.

Biomass vertical distribution has been modelled by use of other nonlinear equations (e.g., Fernandes et al. 2002; Alexander et al. 2004; Reinhardt et al. 2006; and Mitsopoulos and Dimitrakopoulos, 2007). However, the Weibull distribution was chosen here because it has been shown to be successful in modelling the vertical distribution of foliage and branches in studies focused on canopy fuel description (Keyser and Smith 2010) and on branch and (or) foliage distribution throughout the crown (Gillespie et al. 1994; Xu and Harrington 1998).

Since the database contains multiple observations over the length of a stem, it is reasonable to expect autocorrelation within the residuals of each individual, which violates the assumption of independent error terms. This was not taken into account in previous approaches. Autocorrelation was corrected using a modified  $k$ -order autoregressive error structure, which accounted for the distance between measurements ( $h_{ij}/h$ ) for each tree. In this structure, the error terms were expanded as follows:

$$[4] \quad e_{ij} = d_k \rho_k^{h_{ij} - h_{ij-k}} e_{ij-k} + \varepsilon_{ij}$$

where  $e_{ij}$  is the  $j$ th ordinary residual on the  $i$ th individual (i.e., the difference between the observed and the estimated  $W_n(h_i)/W_n$  values of tree  $i$  at an  $h_i/h$  value of  $j$ );  $d_k = 1$  for  $j > k$  and it is zero for  $j \leq k$ ;  $\rho_k$  represents the  $k$ -order continuous autoregressive parameters to be estimated;  $h_{ij} - h_{ij-k}$  are the distances separating the  $j$ th from the  $j$ th -  $k$  observations, with  $h_{ij} > h_{ij-k}$  and  $\varepsilon_{ij}$  representing independent normal random variables with a mean value of zero.

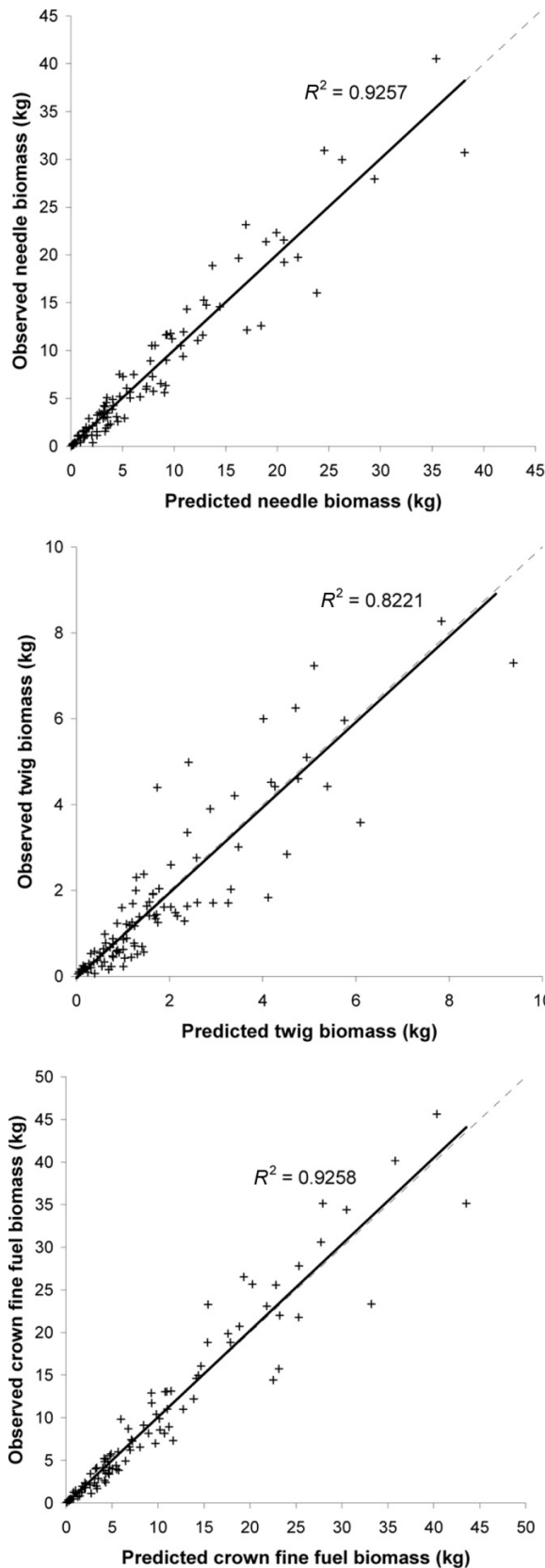
To test for the presence of autocorrelation and the order ( $k$ ) of the modified error structure to be used, graphs representing residuals versus residuals from previous observations within each tree were examined visually.

### Statistical analysis

The five-equation system consisting of the three total biomass equations (needles, twigs, and available crown fuels) and the two biomass ratio equations (needles and twigs) were fitted simultaneously by the iterative seemingly unrelated regression (ITSUR) method, using the SAS/ETS MODEL procedure (SAS Institute Inc. 2004). This approach guarantees compatibility between the estimates of needles, twigs, and total crown fine fuels (sum of needles and twigs) and simultaneously minimizes the errors associated with these equations, while also taking into account the cross-equation correlations. An estimate of the cross-equation error covariance matrix to initiate the iterative procedure was obtained by first using ordinary least-squares.

In the five-equation system, the number of observations in the three total biomass equations and the number of observations in

**Fig. 1.** Plots of observed versus predicted values of needles, twigs, and available crown fine fuel biomass. The solid line represents the linear model fitted to the scatter plot of data and the broken line is the 1:1 line.



the two biomass ratio equations are not equal. There is more than one  $h_j/h$  observation for each tree, but only one observation for needles, twigs, and total crown fine fuels. However, simultaneous fitting of the system requires the number of observations of the independent variables to be equal. To solve this problem, a special structure was created for the data: the needles, twigs, and total crown fine values of the tree were assigned to each  $h_j/h$  observation on the same tree. The inverse of the number of observations for each tree was then used to weight the total biomass equations for each crown fuel fraction in the fitting process (Crecente-Campo et al. 2010).

The modified  $k$ -order autoregressive error structure and the weighting factor for heteroscedasticity,  $1/(X_i)^k$ , and the difference in the number of observations were programmed into the MODEL procedure of SAS/ETS (SAS Institute Inc. 2004). The latter was multiplied, for each dependent variable ( $W$ ), by specifying  $resid.W = resid.W/\sqrt{(X_i)^k n_i^2}$  (note that the residual,  $resid.W$ , is multiplied by  $1/\sqrt{(X_i)^k n_i^2}$  because the latter acts on the residual before it is squared (SAS Institute Inc. 2004).

When the data used to fit the models is artificially modified (by weighting), the approximate standard errors of the coefficients will also be affected. The general expression for correct calculation for the standard errors is as follows (Crecente-Campo et al. 2010):

$$[5] \quad \text{Approx Std Error}_{\text{true}} = \text{Approx Std Error}_{\text{weight}} \sqrt{\frac{N_{\text{weight}} - p}{N_{\text{true}} - p}}$$

where  $N_{\text{weight}}$  is the number of observations used to fit the models,  $N_{\text{true}} = \sum_{i=1}^{N_{\text{weight}}} w_i$ ;  $w_i$  is the weighting factor used to modify the database; and  $p$  is the number of model parameters.

In all cases, the goodness-of-fit was based on numerical and graphical analyses of the residuals. Two statistical criteria were examined: the coefficient of determination for nonlinear regression ( $R^2$ ), defined as the square correlation coefficient between the measured and estimated values ( $r_{Y_i \hat{Y}_i}$ ); and the root mean square error (RMSE). The expressions of these statistics are summarized as follows:

$$[6] \quad R^2 = r_{Y_i \hat{Y}_i}^2$$

$$[7] \quad \text{RMSE} = \sqrt{\frac{\sum_{i=1}^n (Y_i - \hat{Y}_i)^2}{n - p}}$$

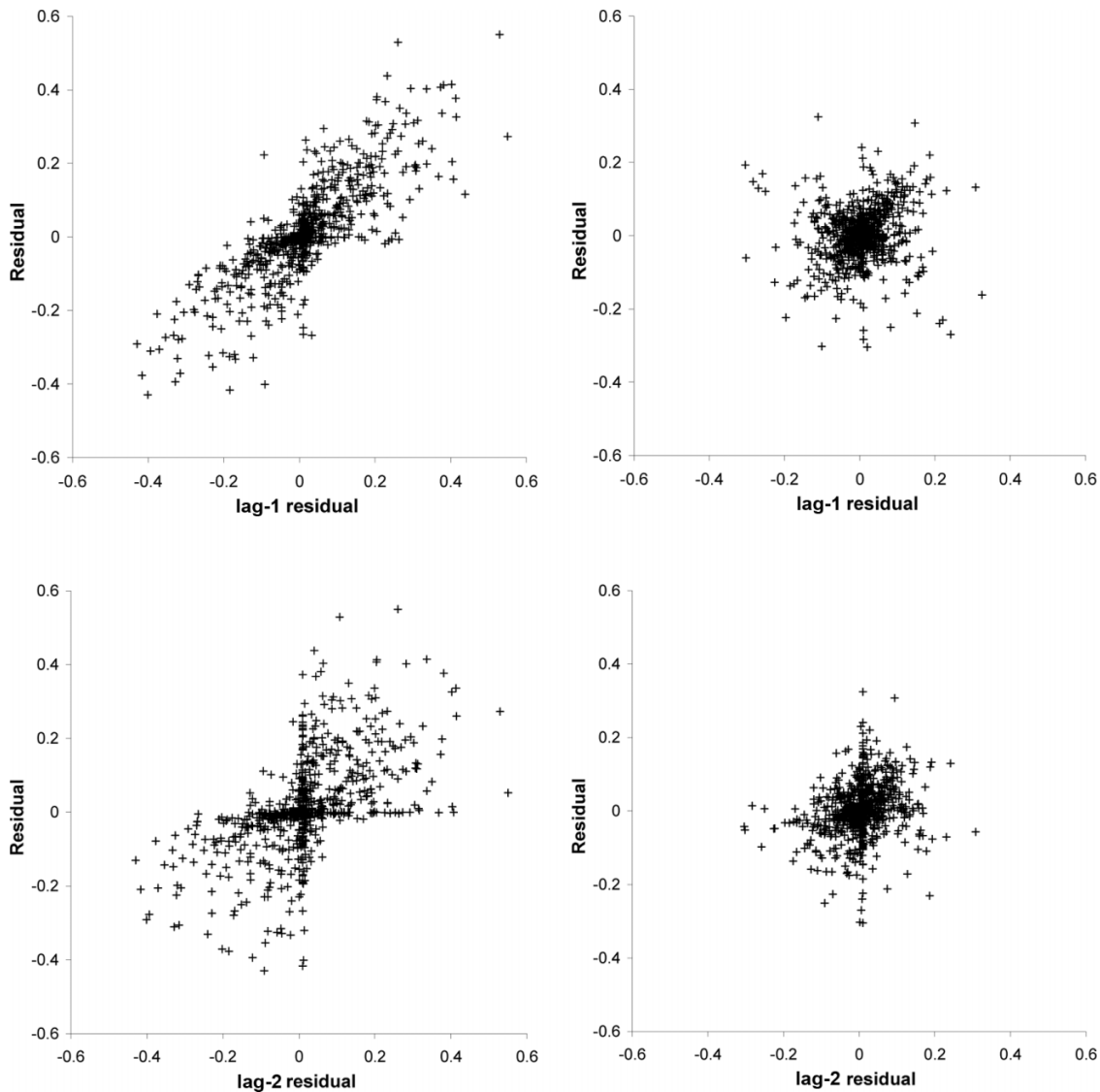
where  $Y_i$  and  $\hat{Y}_i$  are the observed and estimated values of the dependent variable, respectively;  $n$  is the total number of observations used to fit the model; and  $p$  is the number of model parameters.

## Results and discussion

### Total biomass equations for each crown fuel fraction

The allometric models for needles, twigs, and available crown fine fuels were fitted independently, to determine the best set of independent variables. Once the independent variables were selected, a full model (a different set of parameters for each sampled site) and reduced models (developed considering the additional hypothesis of equal site effects) were fitted to evaluate intersite differences. The residuals of the allometric models were then used to check for the presence of heteroscedasticity and, where necessary, correction factors were applied. Finally, the three models and the biomass ratio equations were fitted simultaneously.

Fig. 2. Graphs of biomass ratio residuals plotted versus lag-1 residuals (first row) and lag-2 residuals (second row) for the twig fraction fitted without consideration of the autocorrelation parameters (left column) and with the second-order autoregressive error structure (right column).



The biomass models finally selected for different crown components of maritime pine are shown in Table 3. All equation parameters were significant at the 5% level. Inclusion of weighting factors corrected the heteroscedasticity associated with the raw residuals. The needles and available crown fine fuel models explained more than 92% of the observed variability, and the twig fraction model explained more than 82% of the observed variability (Fig. 1).

Similar goodness-of-fit statistics were obtained in most biomass studies on the same species (Porté et al. 2000; Fernandes et al. 2002; and Shaiek et al. 2011) and on other Mediterranean pine species (e.g., Küçük et al. 2007; Mitsopoulos and Dimitrakopoulos, 2007; and Zianis et al. 2011). DBH appeared to be the best explanatory variable for all the models, which supports the most common mathematical model in biomass studies (e.g., Ter-Mikaelian and Korzukhin 1997).

The inclusion of other dendrometric parameters (height, height-to-crown base, CL, and CW) has been found to improve the fit of biomass equations for pine species (e.g., Claesson et al. 2001; Keyser and Smith 2010; and Shaiek et al. 2011). Moreover, the inclusion of crown size variables should make biomass models less sensitive to differences in competition, as these variables are

tree characteristics influenced by the amount of competition in the neighbourhood (Claesson et al. 2001; Lintunen and Kaitaniemi 2010). In this study, the inclusion of CL as an independent variable improved model estimates for needle and available crown fine fuels. This variable appears to reflect the growing conditions of the tree, with the CL of trees in closed or high-density stands being shorter than that of trees in more open low-density stands. Some authors have also observed the importance of CL or CR in explaining the variability of crown biomass fractions: for needle biomass in *P. pinaster* (Fernandes et al. 2002) and *Pinus taeda* L. (Zhang et al. 2004); for fuel biomass in *Pinus nigra* Arnold and *Pinus brutia* Ten. (Küçük et al. 2007); and for needle and twigs biomass in *Pinus ponderosa* Douglas ex P. Lawson & C. Lawson (Keyser and Smith 2010).

The inclusion of age (in addition to DBH) as an independent variable substantially improved the precision of the twigs model, with a reduction in the RMSE of 17.20%. Age has been also included as an independent variable in allometric equations for different crown fractions in maritime pine (Shaiek et al. 2011) and other species (e.g., King et al. 2007).

Several studies have emphasised the need to consider the influence of stand structure characteristics (basal area, crown position,

**Table 4.** Relative distribution of needles [ $W_n(h_i)$ ], twigs [ $W_t(h_i)$ ] and available crown fuel biomass (needles and twigs) obtained by simultaneously fitting the equation system.

Crown fraction	Model	Parameter	Estimation	Std. error	RMSE
Needles	$\frac{W_n(h_i)}{W_n} = 1 - \exp \left\{ - \left[ \frac{(h_i/h)}{\alpha_{0n} + \beta_{0n}CR + \gamma_{0n}ReID} \right]^{\alpha_{1n} + \beta_{1n}CR} \right\}$	$\alpha_{0n}$	0.913	0.007	0.041
		$\beta_{0n}$	-0.132	0.011	
		$\gamma_{0n}$	0.029	0.006	
		$\alpha_{1n}$	15.089	0.639	
		$\beta_{1n}$	-10.381	1.195	
		$\rho_1$	-0.497	0.030	
		$\rho_2$	-0.208	0.031	
Twigs	$\frac{W_t(h_i)}{W_t} = 1 - \exp \left\{ - \left[ \frac{(h_i/h)}{\alpha_{0t} + \beta_{0t}CR} \right]^{\alpha_{1t} + \beta_{1t}CR + \gamma_{1t}ReID} \right\}$	$\alpha_{0t}$	0.919	0.0161	0.058
		$\beta_{0t}$	-0.367	0.033	
		$\alpha_{1t}$	7.001	0.620	
		$\beta_{1t}$	-7.948	0.842	
		$\gamma_{1t}$	2.206	0.421	
		$\rho_1$	-0.974	0.029	
		$\rho_2$	-0.567	0.034	
Available crown fine fuels	$\frac{W_{n+t}(h_i)}{W_{n+t}} = \frac{W_n}{W_{n+t}} \left( 1 - \exp \left\{ - \left[ \frac{(h_i/h)}{\alpha_{0n} + \beta_{0n}CR + \gamma_{0n}ReID} \right]^{\alpha_{1n} + \beta_{1n}CR} \right\} \right) + \frac{W_t}{W_{n+t}} \left( 1 - \exp \left\{ - \left[ \frac{(h_i/h)}{\alpha_{0t} + \beta_{0t}CR} \right]^{\alpha_{1t} + \beta_{1t}CR + \gamma_{1t}ReID} \right\} \right)$				0.064

**Note:**  $W_n$  and  $W_t$  are the total needle fraction and twig fraction biomass equations (Table 3), respectively; and  $\rho_i$  represents the  $i$ th-order autoregressive parameters. All coefficients were significant at  $p < 0.05$ . CR, crown ratio; ReID, relative dominance; RMSE, root mean square error; and  $h_i/h$ , relative height.

competition indices, and density) on the allometric equations (Reinhardt et al. 2006; Mitsopoulos and Dimitrakopoulos 2007; Lintunen and Kaitaniemi 2010). In the present study, the inclusion of stand variables or competition indices to take into account the differences in density and stand structure did not lead to substantial decreases in the standard error of the estimate, either because they were not significantly correlated with dependent variables or because of multicollinearity problems.

Reinhardt et al. (2006) and Zianis et al. (2011) observed that, although the use of general allometric equations appears promising, site-specific fitting factors are required to provide more accurate predictions. However, in different allometric studies of *Pinus* species, generalized equations have been developed for stands of the same tree species with different site and tree characteristics (King et al. 2007; Shaiek et al. 2011). In the present study, the log-likelihood ratio test only indicated significant differences ( $\alpha = 0.05$ ) for needles and available crown fine fuel models in coastal Galicia. These differences affected the estimated values of parameter “ $a$ ” (eq. [1]) and the parameter associated with DBH. This may be a consequence of the different climatic conditions, especially water availability and temperature (López-Serrano et al. 2005), or may be due to the slightly larger dimensions (diameter and height) of the sampled trees in coastal Galicia. Nonetheless, taking into account the goodness-of-fit obtained with the same set of parameters for all sites and the small number of trees sampled for this area (16 trees), generalized models were preferred for all the crown fractions because of their simplicity. This decision supports the results obtained for *P. pinaster* trees in different environments (ranging from France to Tunisia) by Shaiek et al. (2011), who observed that aboveground biomass equations (based on diameter or a combination of diameter and age as independent variables) were not affected by site conditions, silvicultural practices, or geographical provenance.

**Biomass ratio equations for each crown fuel fraction**

The scale ( $c_0$ ) and shape ( $c_1$ ) parameters of the Weibull function (eq. [3]) fitted to the needle fraction ranged from 0.78 to 0.91 and 5.46 to 26.91, respectively. The values of the same parameters estimated for the twigs fraction ranged from 0.48 to 0.86 and 2.04 to 48.28, respectively. CR and ReID were selected to model the scale and shape parameters for all crown fractions. No other tree

or stand variable was included, and therefore the scale and shape parameters were expanded to include the effect of those two variables for each crown fraction.

$$[8] \quad c_{0 \text{ crown fraction}} = \alpha_0 + \beta_0CR + \gamma_0ReID$$

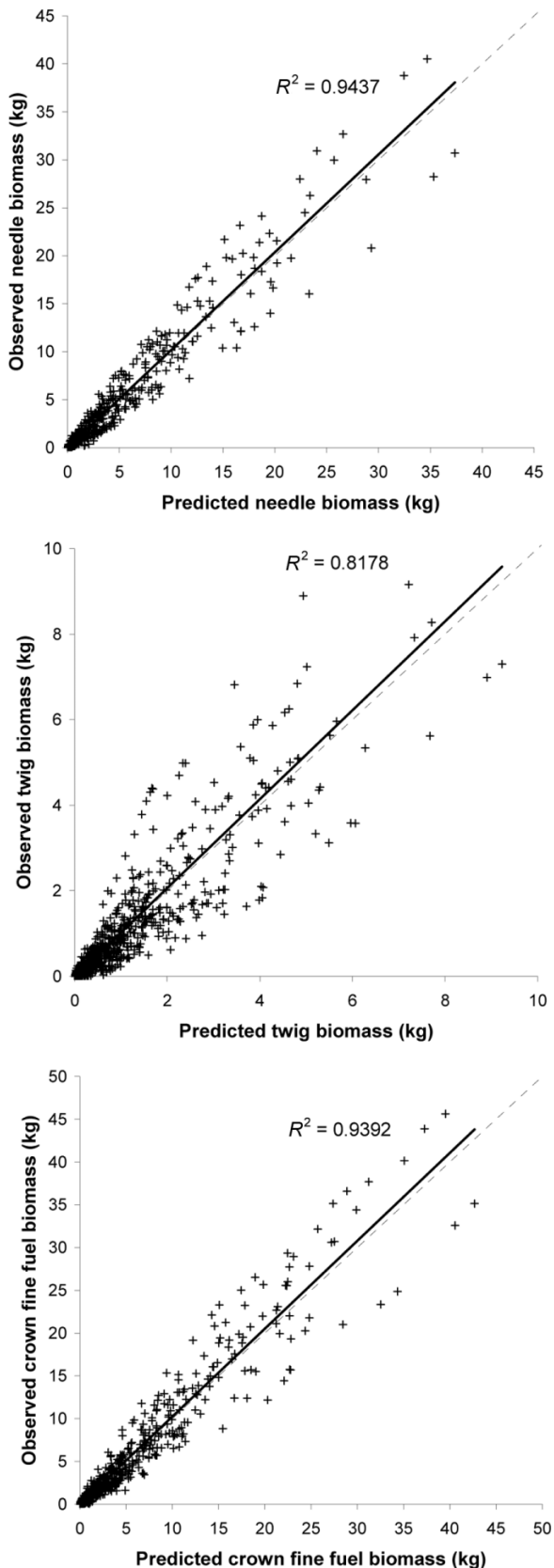
$$[9] \quad c_{1 \text{ crown fraction}} = \alpha_1 + \beta_1CR + \gamma_1ReID$$

After including eqs. [8] and [9] in the Weibull function, the system of equations was fitted simultaneously without expanding the error terms to account for autocorrelation. A trend in residuals as a function of the distance between measurements within the same tree was apparent in the biomass ratio equations of all the crown fractions. A negative correlation between residuals and lag-1 and lag-2 residuals was observed. The observed trend for the twig biomass ratio equation (left column) is shown in Fig. 2. After corrections were made for autocorrelation, with a second-order autoregressive error structure (eq. [4]), the trends in the residuals disappeared (Fig. 2, right column). The estimates provided by the equations were not significantly different from those provided by the equations fitted without considering this type of correction. The sole purpose of autocorrelation correction was to improve the interpretation of the statistical properties of the model and it has no practical application unless several measurements of cumulated biomass at different heights are considered in the same individual tree.

The parameter estimates, their corresponding approximated standard errors, and the RMSE of the biomass ratio equations fitted are shown in Table 4. All the parameters were found to be significant at the 5% significance level, except  $\gamma_{1n}$  (ReID was not significantly related to the shape parameter for needles) and  $\gamma_{0t}$  (ReID was not significantly related to the scale parameter for twigs). The inclusion of CR and ReID as independent variables for estimating the scale and the shape parameters of the Weibull function led to reductions of the RMSEs of estimation of 17.02%, 15.38%, and 16.84% for the ratio biomass equations of needles, twigs, and available crown fine fuels, respectively.

The scatter plots of observed cumulated biomass (kg) against predicted cumulated biomass, obtained by combining the total biomass equations and the biomass ratio equations for each

**Fig. 3.** Plots of observed versus predicted values of cumulated biomass for needles, twigs, and available crown fine fuel. The solid line represents the linear model fitted to the scatter plot of data and the broken line is the 1:1 line.



crown fraction, are shown in Fig. 3. All combined equations accounted for more than 80% of the total variance of cumulated biomass, particularly for needles and available crown fine fuels, which explained more than 93% of the variability (Fig. 4). Similar goodness-of-fit statistics were obtained in other studies, using either the Weibull distribution equation, e.g., for crown fuel biomass of *P. ponderosa* trees (Keyser and Smith, 2010) and for branches and (or) needles of *P. taeda* (Baldwin et al. 1997); or using another nonlinear model, e.g., for needles and (or) branches for *Pinus halepensis* Mill. in Greece (Mitsopoulos and Dimitrakopoulos 2007), for *P. pinaster* in Portugal, (Fernandes et al. 2002), for *Pinus banksiana* Lamb. and *Picea mariana* (Mill.) Britton, Sterns & Poggenb. in Canada (Alexander et al. 2004), and for five conifer species in western inland areas of the US (Reinhardt et al. 2006).

The relative distributions of crown-fraction biomass along tree height depend on the growing conditions and crown class. The maximum values of biomass reached were between 0.6 and 0.8 of relative CH for needles and between 0.5 and 0.7 of the relative CH for twigs, depending on CR and RelD. These values are consistent with those obtained in previous studies on pine species and other conifer species that showed that maximum foliage density is reached in the upper half of tree height (e.g., Baldwin et al. 1997; Porté et al. 2000; Mäkelä and Vanninen 2001; Reinhardt et al. 2006; Keyser and Smith 2010). For the same RelD, trees with low CRs (trees growing under higher stand density) exhibited an upward shift in relative vertical biomass distribution, especially for the twig fraction (Fig. 4, first row). This shift probably occurs as a tree response to the higher light intensity in the upper parts of the canopy in dense stands (Xu and Harrington 1998; Mäkelä and Vanninen 2001). Similar patterns have been observed in other conifer stands (e.g., Garber and Maguire 2005; Reinhardt et al. 2006; Keyser and Smith 2010).

For trees of similar CR, increases in RelD resulted in a slight upward shift of the needle biomass distribution along the tree crown and a higher maximum value of relative biomass for twigs (Fig. 4, second row). Xu and Harrington (1998) observed a similar pattern for foliage biomass of loblolly pine, although the effect of RelD was much more evident than suggested by the results of the present study. However, the strong relationship between CR and RelD complicated analysis of the individual effect of each tree variable.

## Conclusion

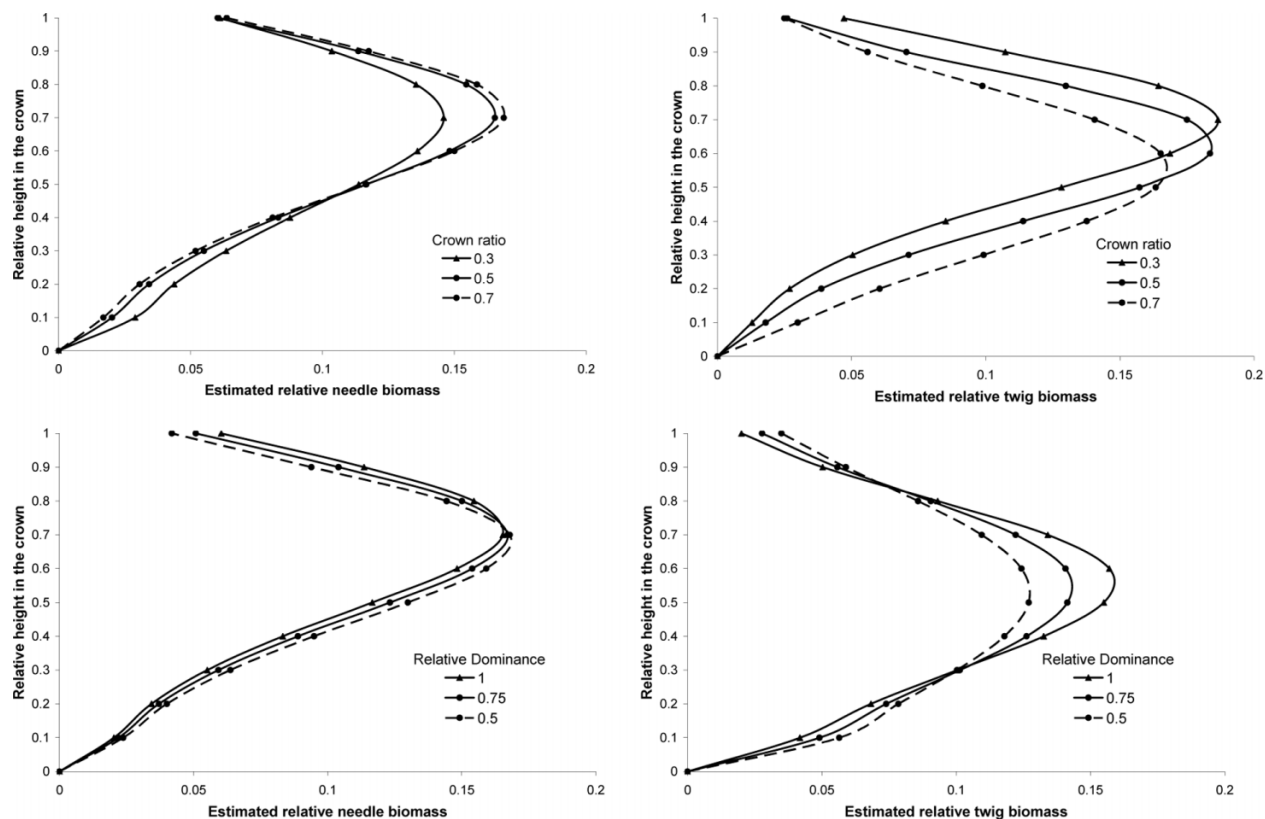
Canopy fuel load (CFL) and canopy bulk density (CBD) are critical in terms of the capacity of this species to sustain active crown fires and are of potential use in different forest management applications, but cannot be measured directly. Indirect methods, based on tree biomass equations and stand characteristics, as analyzed in this study, are a viable alternative.

Autocorrelation of canopy fuels data along tree height was not taken into account in previous studies on relative canopy biomass distribution. Consideration of this factor, along with additivity and simultaneous fitting used in the construction of the equations developed, contributes to improving the quality of canopy fuel assessment. The system of equations obtained provides a reasonably good balance between accurate predictions and low data requirements because it uses some of the most commonly and easily measured variables in forest inventory and age, making it is easy to estimate, as this species is frequently managed in pure and even-aged stands throughout most of the area of distribution.

The results obtained extend the basic information available to date for assessing CFL and CBD in maritime pine to new areas of this species in the Iberian Peninsula. Although not all the provenances of this species have been explored, the information obtained enables estimation of those parameters throughout a large area of the natural distribution of maritime pine. Despite the initial hypothesis, the same equations used to estimate tree



**Fig. 4.** Estimated relative distribution of needle (right column) and twig (left column) biomass along relative tree height for a relative dominance of 1 and different values of crown ratio (first row) and for a crown ratio of 0.5 and different values of relative dominance (second row).



biomass fractions can be applied to the different provenances analyzed, although additional samples must be analyzed to confirm these results.

Moreover, the results clearly showed that vertical crown fuel distribution is not homogeneous within the crown of an individual maritime pine tree, and the shape of the distribution is significantly influenced by the relative crown size of the tree and its dominance status within the stand. This may be critical in physical modelling of crown fire propagation, for which detailed canopy fuel information is required.

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