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Generalized biomass equations for Stone pine (*Pinus pinea* L.) across the Mediterranean basin

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ABSTRACT

Accurate estimates of tree biomass are strongly required for forest carbon budget estimates and to understand ecosystem dynamics for a sustainable management. Existing biomass equations for Mediterranean species are scarce, stand- and site-specific and therefore are not suitable for large scale application.

In this study, biomass allometric equations were developed for stone pine (*Pinus pinea* L.), a Mediterranean tree species with relevant ecologic and economic interest. A dataset of 283 harvested trees was compiled with above- and belowground biomass from 16 sites in three countries (Italy, Spain, Portugal) representative of the species' geographical Mediterranean distribution. A preliminary approach comparing the ordinary least squares method and the mixed model approach was performed in order to evaluate the most appropriate method for nested data in the absence of calibration data. To quantify the sources of error associated with applying biomass equations beyond the geographical range of the data used to develop them, a residual analysis was conducted.

The allometric analysis showed low intra-specific variability in aboveground biomass relationships, which was relatively insensitive to the stand and site conditions. Significant differences were found for the crown components (needles and branches), which may be attributed to local geographical adaptation, site conditions and stand management. The root biomass was highly correlated with diameter at breast height irrespective of the geographical origin. Biased estimates were found when using site-specific equations outside the geographical range from where they were developed.

The new biomass equations improved the accuracy of biomass estimates, particularly for the aboveground components of higher dimension trees and for the root component, being highly suitable for use in regional and national biomass forest calculations. It is, up to the present, the most complete database of harvested stone pine trees worldwide.

1. Introduction

The Global Forest Resources Assessment (FAO, 2016) estimates that the forests and other wooded lands store globally about 369 billion tonnes (Gt) of CO_2 per year. Over the past 25 years, the global carbon stocks have decreased by almost 11 Gt as a consequence of forests conversion to other land uses and, on a lesser extent, to forest degradation (FAO, 2016).

National forest inventories are the worldwide primary source of information about carbon stocks and carbon sequestration, being

therefore an essential tool for defining international agreements regarding the mitigation and adaptation process to climate change. Forest inventory estimates usually rely on species-specific biomass equations and/or biomass expansion factors developed from empirical data. Forest life cycle assessments and carbon footprints accounting are other applications that heavily rely on biomass equation and expansion factors (Demertzi et al., 2016). Therefore, it is of upmost importance to improve the quality of biomass and carbon estimates in order to verify its applicability on large spatial scales (Temesgen et al., 2015).

The development of biomass equations requires harvesting a sample

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of trees, measure them and determine the dry weight of each biomass component. The tree biomass is frequently separated in stem, branches, leaves and roots. Some authors report the branches component by diameter classes as in Porté et al. (2002) or the stem divided in wood, bark and stump (Barreiro et al., 2017). The detail used in biomass separation by components depends on the purpose and mostly on the human and financial resources available. For example, there are substantially less belowground biomass equations because measuring root biomass is more costly and time-consuming than measuring aboveground biomass (Cairns et al., 1997).

Due to tree morphological variability, the allometry between tree biomass and its dimensions tend to be species-specific (Nelson et al., 1999; Teobaldelli et al., 2009). Local environmental conditions (Hulshof et al., 2015), stand management (Cutini et al., 2013) and growing conditions (Naidu et al., 1998; Forrester et al., 2017) also influence biomass growth and their scale ratios. Thus, according to IPCC (2003), it is a good practice to develop species-specific biomass equations with local trees (Temesgen et al., 2015).

Some studies provide biomass equations dependent on stand characteristics (António et al., 2007; Oliveira and Tomé, 2017). However, according to Sileshi (2014), models with multiple predictors may have constrains, such as collinearity or cross-validation problems, and frequently are difficult to interpret from a biological point of view, as compared to simpler models. Typical biomass equations are described by power-law functions that frequently use the diameter at breast height and tree total height as predictors. Sileshi (2014) notice that linear models are also common in the literature although this formulation lacks a biological meaning. This author points that an arbitrary analytical method selection, an inadequate model analysis obtaining ambiguous results are amongst the most frequent mistakes on biomass equations formulation.

Despite the variety of proposed approaches, the end-user very often prefers to adopt existing biomass equations from literature rather than harvesting trees to develop new biomass equations. However, as published biomass equations are usually based on a small number of harvested trees covering a limited diameter classes range (Clark and Clark, 2000), there is a potential problem of applying these equations beyond the allometry range for which they have been developed. Chave et al. (2004) recommend to avoid the development of models from a small sample, indicating a minimum number of 100 harvested trees, while Sileshi (2014) suggests a minimum sample size of 50 trees.

Notwithstanding the above considerations, equations for estimating biomass and carbon stock are still the most frequently adopted tool, due to the possibility to develop biomass estimations from forest inventory data. A recent study from Forrester et al. (2017) provides generalized biomass equations for 24 European tree species, unfortunately, neglecting many Mediterranean species such as Stone pine. This species is native from the Mediterranean basin, covering about 750,000 ha (Fady et al., 2004), with a recent increasing expansion through forest restauration or farmland afforestation (Mutke et al., 2012). Its economic interest is high due to the production of edible nuts, with current retail prices close to 100 €/kg. In fact, it has been used for many centuries for cone production but also in the recovery of lowland areas and in the protection of coastal dunes (Mutke et al., 2012). Stone pine have a high level of phenotypic plasticity, is demographically widespread but shows a remarkably low genetic diversity (Mutke et al., 2005; Vendramin et al., 2008). It appears either in arid inland or coastal sea areas affected by salinity stress and can potentially help in mitigating desertification problems in these areas. As a moderately drought-tolerant species, it is also of great interest in afforestations in a context of climate change (Correia et al., 2010). At the present, Stone pine has attained a high ecological, recreational and landscape value (Mazza et al., 2011).

Site-specific biomass equations and expansion factors for Stone pine have already been developed from harvested trees collected in Italy by Cutini et al. (2013), in Spain by Montero et al. (2005), Ruiz-Peinado et al. (2011) and Portugal by Correia et al. (2010). In this study, the data collected from the above studies were integrated and expanded, originating the largest and a unique biomass dataset for Stone pine, which has been used to develop allometric biomass (both aboveground and belowground) equations for the species, along its ecological and geographical Mediterranean range. The study specific objectives are: (1) to compare biomass relationships between trees growing in different ecological regions and management contexts; (2) to develop a system of biomass equations for aboveground and belowground biomass for the Mediterranean Stone pine and (3) to quantify the sources of error in biomass estimates associated with the use of biomass equations developed beyond their ranges of stand, site and climate conditions.

2. Material and methods

2.1. Data organization

The dataset contains biomass information obtained in harvested trees from three Mediterranean countries: Italy (IT), Portugal (PT) and Spain (SP) which were sampled in previous studies (Cutini et al., 2013; Ruiz-Peinado et al., 2011; Correia et al., 2010), either for aboveground and belowground biomass and also new data which have been collected under the current study. The final dataset contains measurements carried out in 283 trees, sampled in 16 sites located across the species' geographical range (Fig. 1).

For each country, the published studies contain a detailed description of the sampling protocol used for harvesting, measuring tree biomass and separating total biomass into different components. The sampling procedures are considered comparable between the countries regardless small differences related with the separation of branches by dimensions; bark separation from the trunk; and inclusion of thin roots. Each country used the same methodology for the belowground quantification, by removing the stump and roots within an area of approximately the crown projection, however for Spain the thin roots were not included.

Tree information regarding the diameter at breast height (d) and total height (h) was available for all sites (Table 1), with exception of Almonte site in Spain where tree height (h) was not measured. Total aboveground biomass (wa) was available for all sites, and corresponds to the sum of the tree aboveground components: stem, that includes wood and bark (ws) and excludes the stump not removed from the soil; branches (wbr) and needles (wl). Belowground biomass (wr), corresponding to the tree root system that includes the stump, was only available in some sites, for a total of 74 trees (Table 1). Stand data include stand age (t), stand density (N), mean temperature (T, in °C) and mean precipitation (P, in mm) (Table 1). No quantitative measurement of the stand density was available for the Spanish sites (SP) with only the information of tree competition within each stand by expert assessment.

2.2. Development of a system of biomass equations suitable to the whole Mediterranean region

A new system of equations was developed using the Mediterranean dataset collected from the three Mediterranean countries. Some trees were excluded because not all the tree components were available in some of the sites, namely tree height in Almonte and needle biomass in Roman Coast (see Table 1). The selection of the harvested trees was performed taking into consideration the diameter and approximate age classes distribution. Some trees were harvested from the same site. The equation used to model each tree biomass component was:

$$w = kd^{\alpha}x^{\beta} + \epsilon$$

where w is the total aboveground biomass or one of its component (branches, needles, stem or roots), k is the allometric constant, α and β are the allometric parameters, d is the tree diameter at breast height, x is an additional tree variable or a combination of variables and ϵ is the
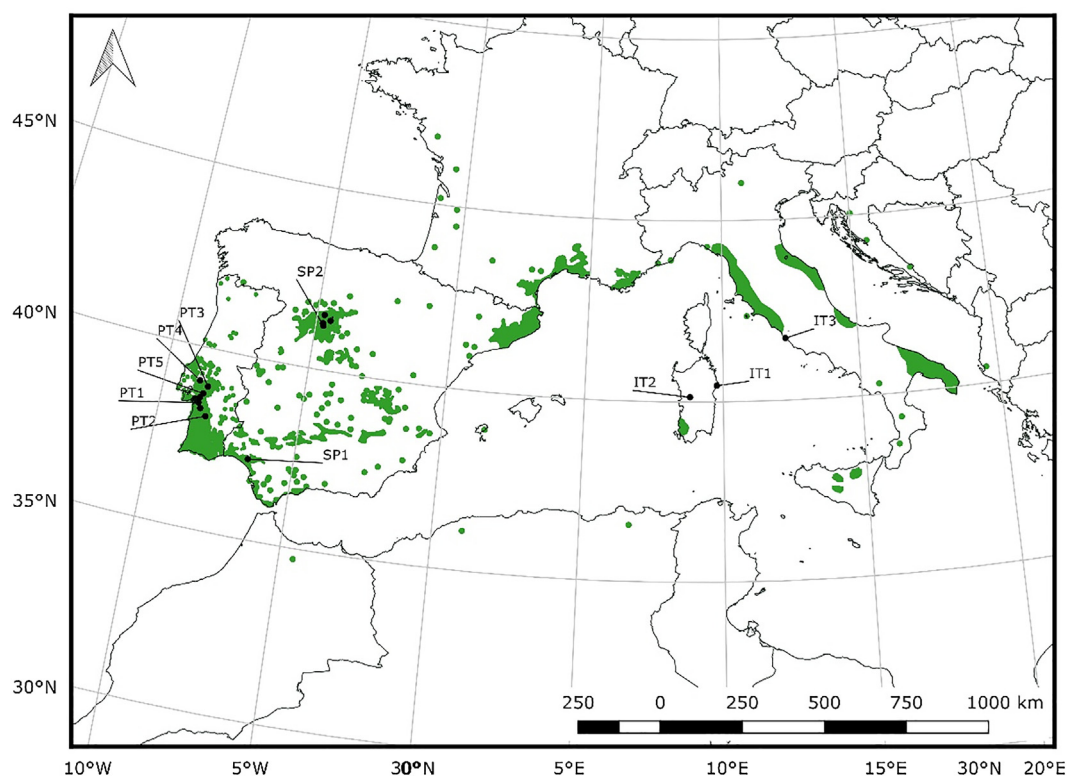
Fig. 1. Stone pine distribution in the Mediterranean basin (green) (Fady et al., 2004). The black dots identify the locations from where the trees were harvested. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

additive error term.

Tree height was not always measured in the field, therefore two systems of equations were fitted. One system uses only d (MT-d) as independent variable and the other system uses both tree d and h (MT-dh).

2.2.1. Comparing the ordinary least squares method and the mixed model approach

Due to the nested structure dataset, with several trees harvested in the same site, the use of a mixed models *versus* ordinary least squares may be considered. According to Huang et al. (2013) the ordinary

nonlinear least squares method is the most accurate method in making population average predictions and more suitable when the model is used for prediction in the absence of measurements for the calibration process. Other studies have also shown that when the calibration process is not performed, the nonlinear fixed effect model results in lower prediction errors than the mixed effect model (Paulo et al., 2011, 2015; de-Miguel et al., 2013). This topic is not however consensual (Poudel and Temesgen, 2016).

Due to the debate on the most accurate method to develop a model from a nested structure dataset for future predictions in the absence of data for calibration, a preliminary assessment of two approaches was

Table 1
Main attributes of sites, reporting the number of harvested trees for aboveground biomass sampling (Nr of trees) followed by the number of trees with belowground biomass (in brackets). Average values are presented for the following stand and tree variables: N, number of trees per hectare; t, stand age (years). Minimum and maximum values are presented for the folowwing variables: ; d, tree diameter at breast height (cm); h, tree height (m); wa, tree aboveground biomass (kg); wr, tree belowground biomass (kg); T, average long term air temperature (°C); P, long term yearly total precipitation (mm). (* is for stands in competition and empty cells means no data). The letters (a) and (b) following the ID country identification represents different locations in the same region.

Country	ID	Sites	Lat; Long	Nr trees	t (years)	N (ha)	d (cm)	h (m)	wa (kg)	wr (kg)	T (°C)	P (mm)
	IT1	Bidderosa	40°27 N, 9°46 E	20 (6)	48	462	12; 34	5.9; 10.2	22; 438	28; 79	16.6	536
Italy	IT2	Is Arenas	40°08 N, 8°48 E	25 (8)	60	639	10; 40	6.9; 12.7	28; 883	7; 78	16.9	599
	IT3	Roman Coast	41°43 N, 12°19 E	32	56	354	15.5; 49	14.1; 18.9	–		16.2	709
	PT1 (a)	Monte Novo	38°28 N, 8°38 W	5	Uneven	110; 130	29.4; 43.2	11; 12	476; 750		16	572
	PT1 (b)	Valverde	38°19 N; 8°31 W	10	25; 31	713; 978	6.3; 30.7	5.7; 11.1	8; 238		16.3	574
Portugal	PT2	Ferreira Alentejo	38°08 N; 8°18 W	4	Uneven	74; 170	9.2; 30.9	2.7; 10.1	26; 348		16.2	586
	PT3	Coruche	38°57 N; 8°25 W	6 (6)	Uneven	20; 90	6.5; 46	2.1; 7.7	20; 1202	7; 217	16	642
	PT4	Escaroupim	39°04 N; 8°44 W	20	14; 15	491; 605	6.3; 20.2	2.6; 60	17; 178		16.0	642
	PT5 (a)	Espirra	38°37 N; 8°37 W	15	Uneven	53; 111	8; 56.3	3.7; 17.3	17; 2177		15.9	709
	PT5 (b)	Abegoaria	38°44 N; 8°31 W	5	Uneven	20; 24	59.2; 72.6	12.4; 15.1	1899; 3969		15.9	709
	PT5 (c)	Gâmbia	38°33 N; 8°47 W	10	20	580	7.4; 20.4	2.6; 5.9	15; 113		16.1	735
	SP1	Almonte	37°13 N; 6°34 W	35 (13)	Uneven	*	7.5; 63	–	25; 4026	6; 777	18.2	525
	SP2 (a)	Olmedo	41°17 N; 4°45 W	41 (41)	17	*	8.6; 18.3	3.3; 6.5	17; 152	3; 36	12.7	417
Spain	SP2 (b)	Bocigas	41°13 N; 4°43 W	20	Uneven	*	11.3; 57	5.6; 17.3	33; 1813		12.2	400
	SP2 (b)	Iscar	41°23 N; 4°29 W	12	Uneven	*	9; 29	4.3; 10.3	17; 290		12.3	447
	SP2 (b)	Viana de Cega	41°31 N; 4°44 W	22	Uneven	*	12; 62	6.2; 21.2	24; 2225		12.5	376

Table 2

Published site-specific systems of biomass equations, fitting dataset d range (cm) and correspondent evaluation statistics. Abbreviations stand for: d, tree diameter at breast height (cm); c, circumference at breast height (cm); h, tree height (m).

Country	Biomass component	Model	Published statistics
Italy (IT)	Stem	$0.091\,d^{2.346}$	RMSE = 70.85
d range: [10–50]	Needles	$0.009\,d^{2.537}$	RMSE by local 3.91;16.39; 2.74;4.93
Cutini et al. (2013)	Woody	$0.045\,d^{2.602}$	RMSE = 85.14
	Aboveground	Σ components	
Portugal (PT)	Wood	$18.85c^{1.68}h^{0.95}$	$r^2aj = 0.93$
	Bark	$8.08c^{1.55}h^{0.47}$	$r^2aj = 0.82$
d range: [7–56]	Needles	$22.27c^{1.76}\,(h/d)^{(-0.5)}$	$r^2aj = 0.63$
	Branches	$184.94c^{3.03}$	$r^2aj = 0.74$
Correia et al. (2010)	Aboveground	Σ components	
Spain (SP)	Stem	$0.0224\,d^{1.923}h^{1.0193}$	$r^2aj = 0.99$
			RMSE = 36.76
	Needles with thin branches (< 2 cm)	$21.927 - 2.827\,h + 0.0707\,d^2$	$r^2aj = 0.90$
			RMSE = 19.65
d range: [9–63]	Medium branches (2–7 cm)	$0.0525\,d^2$	$r^2aj = 0.80$
			RMSE = 29.46
	Thick branches	$[0.247\,(d-22.5)^2]\,Z$	$r^2aj = 0.86$
Ruiz-Peinado et al. (2011)		If d ≤ 22.5 cm then Z = 0;	RMSE = 46.17
		If d > 22.5 cm then Z = 1	
	Aboveground	Σ components	
	Roots	$0.117\,d^2$	$r^2aj = 0.98$
			RMSE = 14.86

conducted using a fixed effect *versus* a random effect model, using the site as the random effect. The random effect was tested on each one of the parameters at a time or in more than one parameter. This preliminary study was undertaken for the roots and total aboveground biomass using the SAS macro NLINMIX (SAS Institute Inc.). The selection of the best mixed effect model was conducted by comparing the Akaike information criterion (AIC) and the root mean square error (RMSE) values. The comparison of the fixed effect and the best mixed effect models was based on the press residuals (Myers, 1990): mean of the press residuals (Mrp) and mean of the absolute value of the press residuals (Marp) to evaluate bias and precision, respectively (Soares et al., 1995). Model efficiency (MEF) that is, the proportion of variability explained by the model and computed with press residuals, was also used as an additional criteria for model evaluation.

2.2.2. Independent fitting

Based on the results from the preliminary study described in the previous section (see the results section), ordinary nonlinear least squares were selected to fit the biomass models. As a first step, different nonlinear models were individually fited with the PROC NLIN procedure of SAS software 9.4 (SAS Institute Inc.) for each biomass component (stem, branches, needles and roots), using as dependent variables tree diameter (d) and/or tree height (h). To address heteroscedasticity, the methodology proposed by Parresol (2001) was adopted. The non-normality of the errors was overcome with iteratively reweighting least squares regression using the Huber function to reduce the influence of data points containing large errors on the fit (Myers, 1990). The performance of each biomass equation was evaluated using statistics based on the press residuals (Myers, 1990) as in Soares et al. (1995).

2.2.3. Simultaneous fitting with the additivity property

As a final step, the models selected for each tree aboveground biomass component were fitted using nonlinear joint generalized least squares regression, known as iterative seemingly unrelated regression (ITSUR), using the PROC MODEL procedure of SAS software 9.4 (SAS Institute Inc.). In the system of equations, total aboveground biomass was expressed as the sum of the tree components equations, thus guaranteeing the additivity property (estimates of the total aboveground biomass are equal to the sum of the estimates of each of the aboveground biomass components). The initial parameters and weight values for the simultaneous fitting were the ones obtained in the individual fitting of each equation. This technique guarantees that total

aboveground biomass is the sum of the tree aboveground component estimations.

2.2.4. Evaluation of the Mediterranean systems of equations

The evaluation of the predictive performance of the equations, or model validation of both systems (MT-d and MT-dh), was carried out with a resampling procedure. Each system was fitted 11 times with a data set excluding one of the sites described in Table 1, except the ones not used for model fitting, and prediction residuals were computed with the data not used in the fitting step. The validation criteria were based on all the prediction residuals obtained in the 11 fittings, assessing model bias (Mres) and model precision (Mares).

2.3. Site-specific biomass equations

The biomass sampling protocol, and therefore the resulting biomass equations, showed little differences between the countries, namely: the separation of wood and bark in the Portuguese system; the combination of thin branches (diameter < 2 cm) and needles biomass in the Spanish system; and the inclusion of branches biomass together with the woody biomass in the Italian system. The Spanish branches component was separated in three diameter categories and thus the resulting model formulation differed from the function considered in the other countries and components.

A residual analysis was performed to compare the accuracy of each site-specific biomass equations (Table 2) and of the new developed Mediterranean system of equations. This was achieved by assessing the residuals (res) computed through the difference between the observed and the predicted values, using the Mediterranean dataset as a whole and separately for each country. The evaluation statistics for each published site-specific biomass equations were also included in Table 2. The mean of the residuals (Mres) was assessed to evaluate model bias and the mean of the absolute values of the residuals (Mares) to evaluate model precision.

3. Results

3.1. Allometric relationships between biomass and tree variables

The Mediterranean dataset covers d classes from less than 10 cm to over 60 cm (Fig. 2), with the higher number of trees within the 10–20 cm class. Data from Portugal and Spain cover all the diameter
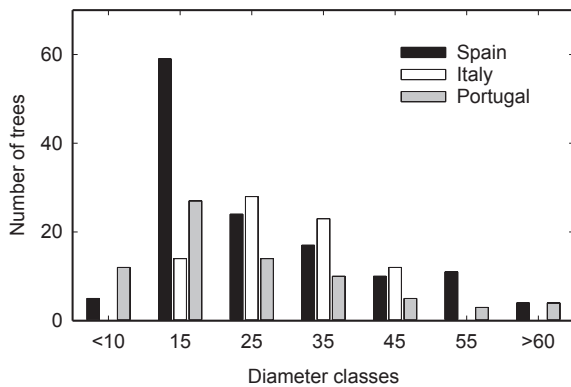
Fig. 2. Distribution of the harvested trees through the diameter at breast height classes.

classes while data from Italy are distributed across the central classes. The larger diameters classes (d > 50 cm) represent only 10% of the total harvested trees.

The tree variables that best describe aboveground biomass variability are d (Fig. 3a), h (Fig. 3b) and tree slenderness (h/d) (Fig. 3c). All biomass components showed an increasing trend with d regardless the geographical origin of the trees (Fig. 3a). Regarding *h*, the relationship seems more variable and probably associated with the lack of information on this attribute for the largest trees in a Spanish site (Fig. 3b). Tree aboveground biomass decreases with the slenderness index, a morphological variable related with tree stability, meaning that d increases more than h as the tree get older and heavier. This is mechanically advantageous, as typically the branches in Stone pine tend to grow laterally in a very prominent way.

A good correlation was found between all the biomass components and d (Fig. 4). A good relationship, but negative, was also found with the needles-to-woody biomass ratio (Fig. 4e). The highest variability was observed for needles and branches namely for the Portuguese trees with diameter over 60 cm and the high branches biomass in the Spanish trees for d over 40 cm. The same tendency was observed for the total needle biomass (Fig. 4f). The needle to-woody-biomass ratio stresses an important functional trait related to the maintenance cost of the living biomass. The decreasing tendency observed with diameter was expected as tree grows, due to the accumulation of standing biomass. However, for the Italian dataset a very low and practically constant ratio below 0.1 was observed for all diameter classes, revealing tree crowns with very few needles in relation to the woody biomass. Scattered trees from Portugal, on the other hand, seem to maintain a higher fraction of needles to woody biomass.
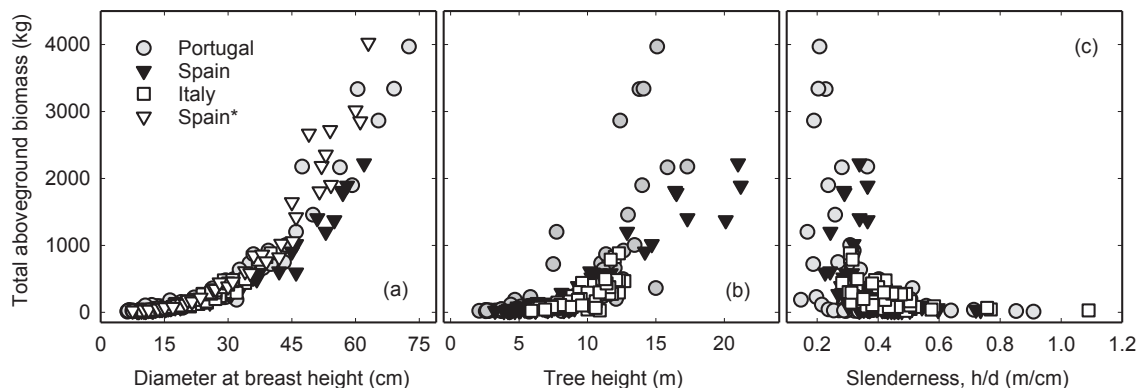

Fig. 4. Relationship between diameter at breast height and biomass by component: (a) Needles, (b) Branches, (c) Stem, (d) Roots, (e) Crown and also the (f) needles–to-woody biomass ratio by country. Portugal (grey circles), Spain (black triangles) and Italy (white squares).

3.2. Development of a Mediterranean system of biomass equations

3.2.1. Comparing ordinary least squares and the mixed model approach

The best performance was achieved for models with the random effect in the allometric constant (k k_μ_0) and it was not possible to add random effects in more than one parameter (Table 3).

Table 4 shows the results from the preliminary study that was undertaken to compare model predictive performance for fixed-effect and mixed models. The fixed effects models with d and h as independent variables (MT-dh) is clearly less biased and more precise than the random effects models, especially in the case of the aboveground biomass. The same result was obtained for the MT-d model for root biomass while the MT-d random effect model for the total aboveground biomass was slightly less biased but with a similar precision. As a consequence the fixed effects models were used for the development of the systems of equations.

Fig. 3. Relationship between aboveground biomass and tree variables: (a) diameter at breast height (d, cm), (b) tree height (h, m), and (c) slenderness (h/d). The * represents trees from Spain whose height was not measured.
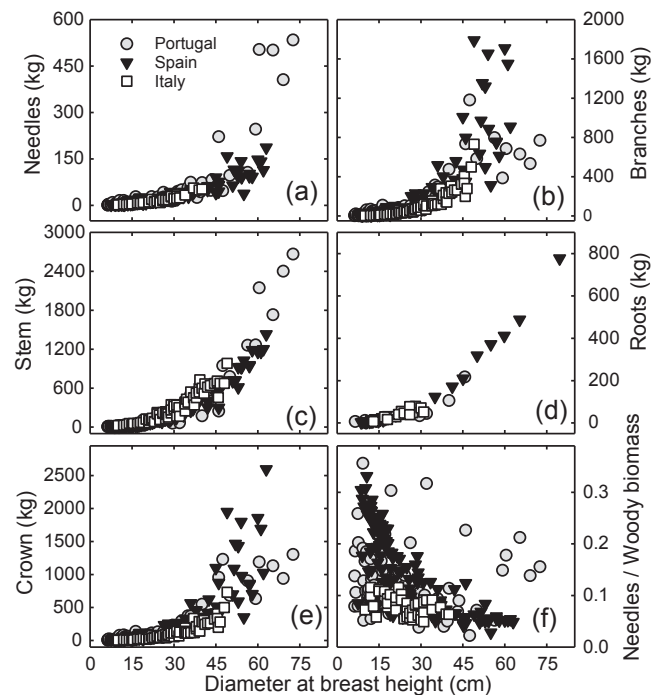
Table 3
Parameter estimates and variance components of the selected models for total aboveground (wa) and root biomass (wr), where (MT-d) includes only tree d (cm), (MT-dh) includes also tree h (m), where RMSE is in kg.

		Fixed effects model				Random effects model			
				Confidence interval				Confidence interval	
		Estimates	p-value	Lower	Upper	Estimates	p-value	Lower	Upper
MT-d for wa	k	0.02718	< 0.0001	0.01658	0.03778	0.04255	< 0.0001	0.02473	0.06037
	α	2.76820	< 0.0001	2.6717	2.8646	2.65990	< 0.0001	2.5493	2.7706
	k_μ_0	–	–	–	–	0.00003	–	0.00001	0.00016
	cov.	13,705	–	11,429	16,740	8,293.41	–	6,895.1	10,167
		AIC = 2,664.2; RMSE = 116.5				AIC = 2,573.8; RMSE = 118.1			
MT-d for wr	K	0.02655	< 0.0001	0.01758	0.03553	0.03865	< 0.0001	0.02405	0.05325
	α	2.35390	< 0.0001	2.2724	2.4354	2.23550	< 0.0001	2.1357	2.3352
	k_μ_0	–	–	–	–	0.000023	–	0.000007	0.00038
	cov.	210.54	–	155.71	300.61	150.6	–	110.77	216.69
		AIC = 624.7; RMSE = 14.3				AIC = 607.0; RMSE = 21.3			
MT-dh for wa	k	0.1756	< 0.0001	0.1145	0.2367	0.1245	0.0002	0.06096	0.1881
	α	1.8192	< 0.0001	1.6833	1.955	1.5861	< 0.0001	1.3231	1.8491
	β	0.6437	< 0.0001	0.4446	0.8429	1.2091	< 0.0001	0.8703	1.5479
	k_μ_0	–	–	–	–	0.001329	–	0.000588	0.005311
	cov.	2.486	–	2.0723	3.0379	1.6556	–	1.3739	2.0343
		AIC = 2,596.3; RMSE = 216.5				AIC = 2,534.1; RMSE = 242.4			
MT-dh for wr	K	0.03459	< 0.0001	0.02325	0.04594	0.03221	0.0002	0.01602	0.04839
	α	2.1057	< 0.0001	1.9573	2.254	2.0588	< 0.0001	1.8049	2.3127
	β	0.2620	0.0005	0.119	0.405	0.3474	0.0115	0.08042	0.6144
	k_μ_0	–	–	–	–	0.000008	–	0.000001	0.02951
	cov.	176.27	–	130.11	252.36	2.3828	–	1.7484	3.4397
		AIC = 613.8; RMSE = 13.0				AIC = 580.0; RMSE = 13.4			

Table 4
Validation statistics computed with press residuals.

		Fixed effects model			Random effects model		
		MEF	Mrp	Marp	MEF	Mrp	Marp
MT-d	wa	0.957	10.686	59.350	0.961	− 5.137	58.169
	wr	0.983	− 0.598	8.675	0.978	2.609	10.177
MT-dh	wa	0.857	17.749	82.935	0.826	− 55.988	117.530
	wr	0.985	− 0.749	9.002	0.983	0.685	9.480

Table 5
Evaluation statistics of the fixed effect models for the biomass components equations, where MT-d includes only tree d (cm), MT-dh includes also tree h (m), where RMSE is in kg.

	MT-d		MT-dh	
Tree component	r^2aj	RMSE	r^2aj	RMSE
Stem	0.926	101.4	0.918	106.5
Branches	0.846	66.8	0.854	65.1
Needles	0.764	33.9	0.887	23.4
Aboveground	0.959	118.7	0.961	115.7

3.2.2. Independent fitting

Tree d was the variable that showed the best correlation with all biomass components. The inclusion of height increased the model performance for the needles, branches and roots components. Comparing the individual fitting, the model efficiency for the needles and branches components increased with the inclusion of h in the model, while it slightly decreased for the stem component (Table 5).

3.2.3. Simultaneous fitting

The higher model efficiency, combining all aboveground biomass components, was obtained with the formulation including both the independent variables d and h (Table 5), which was analysed in detail regarding the residual analysis. However, since the evaluation statistics from MT-d and MT-dh do not differ greatly, the system using d is also shown (Table 6). Considering the MT-dh, the needles equation included the variable slenderness (h/d) in line with the Portuguese equation published in Correia et al. (2010). The model efficiency from the needles and branches components increased for both developed systems, when compared with the Portuguese equations. This is due to the inclusion of an additional 35 harvested trees which were not available in the previous study in Correia et al. (2010).

3.2.4. Evaluation of the Mediterranean systems of equations

Figs. 5 and 6 show the statistics for the prediction residuals obtained with the resampling procedure used for model validation, for each one of the fittings and for the whole set of prediction residuals. The MT-dh bias and precision (Figs. 5 and 6) is generally better for all the fittings except for one site PT5b). The overall bias and precision (last bars) is also higher for the MT-dh models.

3.3. Accuracy of site-specific systems of biomass equations

Fig. 7 illustrates the residual analysis obtained from the most efficient aboveground biomass model that includes both the independent variables d and h (Table 6). Regardless the site-specific biomass equation systems, the residuals (res) for total aboveground biomass (Fig. 7) showed higher bias for the highest diameter classes (d > 50 cm), and the lower classes (d < 30 cm) having a similar prediction performance. Note that the class representing the largest harvested trees (d > 50 cm) have only 24 trees compared with 109 trees from the lower class (d < 20 cm).

The Italian system (IT) presented the lower bias from the country published site-specific equations compared to the higher bias from the Spanish system (Fig. 7). The new Mediterranean system of equation provided more accurate estimates because the number of larger trees increased in the fitting dataset. Therefore, the new Mediterranean

Table 6
Formulation of the Mediterranean system of biomass equations for the aboveground biomass, where MT-d includes only tree d (cm), MT-dh includes tree d and h (m), and RMSE is in kg. For each parameter, the significance (p-value) is presented.

	Biomass component	Model	k	α	β	r²aj	RMSE
MT_d	Stem	k d^α	0.002423 (< 0.0001)	3.246929 (< 0.0001)		0.931	98.2
	Branches	k d^α	0.618358 (< 0.0001)	1.678759 (< 0.0001)		0.797	76.7
	Needles	k (d/100)^α	2061.774 (< 0.0001)	4.248054 (< 0.0001)		0.776	33.0
	Aboveground	Σ components				0.961	115.7
MT-dh	Stem	k d^α (h/d)^β	0.008797 (< 0.0001)	2.871281 (< 0.0001)	−0.19326 (0.0008)	0.930	98.9
	Branches	k d^α h^β	0.060502 (0.0026)	1.897782 (< 0.0001)	0.527179 (< 0.0001)	0.852	65.5
	Needles	k (d/100)^α (h/d)^β	49.37346 (< 0.0001)	2.528243 (< 0.0001)	−2.01953 (< 0.0001)	0.888	23.4
	Aboveground	Σ components				0.960	116.9

system (MT-dh) slightly overestimated aboveground biomass for the higher classes, in contrast with the Spanish system (SP) where it underestimated biomass for that diameter classes (Fig. 8), confirmed when testing the mean residual against zero, with a *t*-Test.

When applying the new Mediterranean equations individually to each country dataset, the needles component biomass provides the higher precision, in terms of mean absolute error (Fig. 9). The same trend was observed for the Portuguese system (PT) applied to the Spain (SP) and Italy (IT) dataset (Fig. 9). Note that the PT system did not fit well to the Portugal dataset, because in this study the dataset from Portugal includes additional 35 harvested trees, already mentioned earlier. The stem and branches biomass components (woody biomass) are shown together because, the published IT equations do not separate these two components (Fig. 9). The MT, the PT and IT equations presented similar precision for the woody biomass component applied to each country dataset. The lowest precision was obtained when applying the SP equations to the Portuguese dataset.

4. Discussion

4.1. Intra-specific variability between countries

The diameter at breast height (d) is the most important variable explaining biomass variability for Stone pine irrespective of the tree component (Fig. 4), in agreement with previous studies (e.g. Correia et al., 2010). This allometric relationship is the most commonly used in the biomass allometry literature (Zianis et al., 2005) and hinges on the well-established relationship between sapwood, the hydraulic conductive area of the stem cross-section, and the amount of leaf biomass or area (Mencuccini and Grace, 1995). The higher the sapwood (here surrogated by the stem diameter), the higher the capacity for leaf area support, photosynthetic production and therefore growth (Rennolls, 1994; Kostner et al., 2002; Ryan et al., 2006). The use of a single, easy to measure variable in biomass equations is advantageous, especially when it is able to explain much of the tree biomass variability. However, for the Stone pine, characterized by a lack of apical dominance, total height is also important. In Stone pine, branches tend to grow
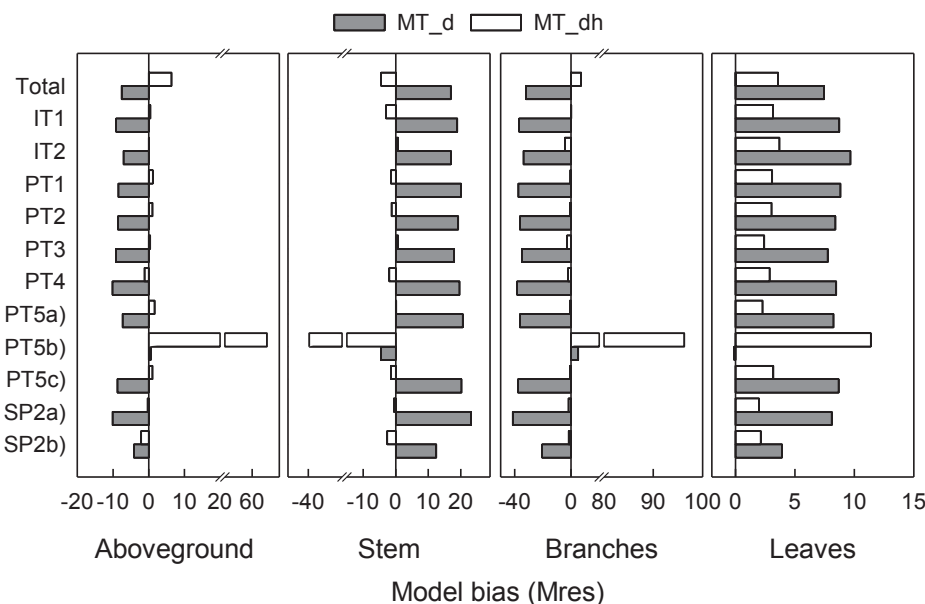

Fig. 5. Mean error of the Mediterranean systems of biomass equations (Table 6) obtained by excluding one site (Table 1) at each fitting.
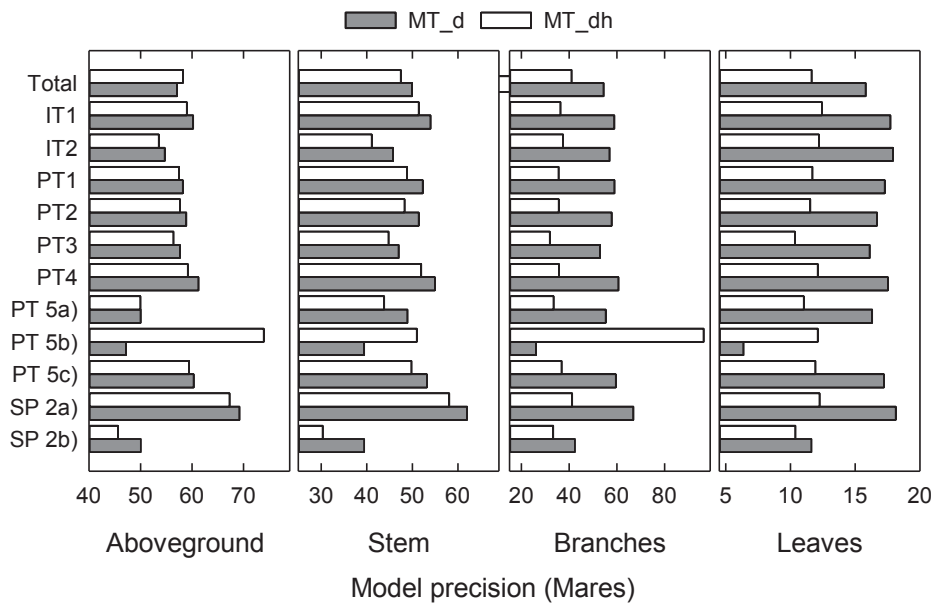
Fig. 6. Mean absolute error of the Mediterranean systems of biomass equations (Table 6) obtained by excluding one site (Table 1) at each fitting.
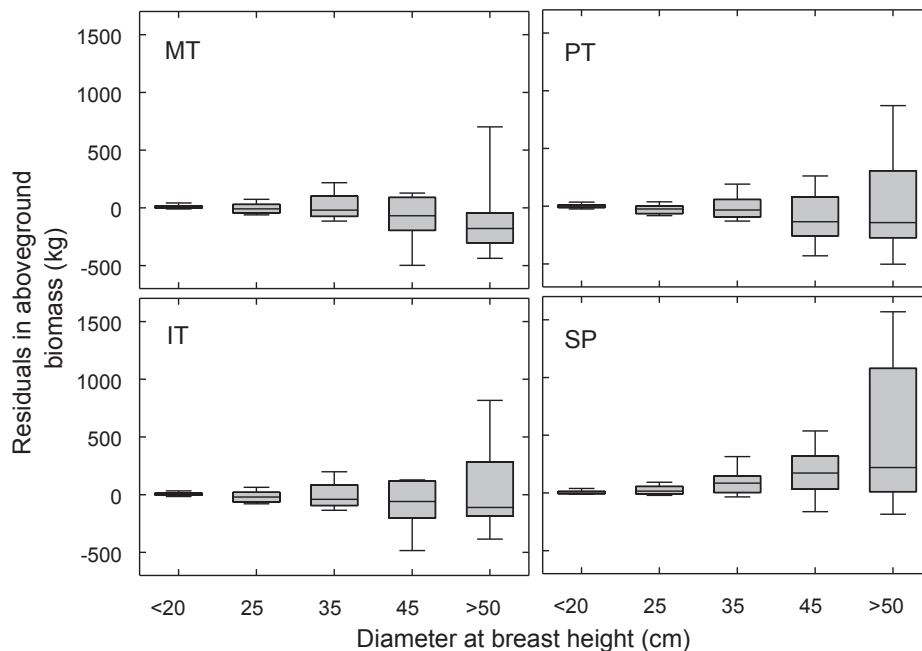

Fig. 7. Distribution of the residuals for total aboveground biomass obtained with each system of biomass equations: IT, Italy; PT, Portugal; SP, Spain ; MT, Mediterranean; applied to the Mediterranean dataset.

laterally in a very steep way, which originates its characteristic umbrella shape. The weight of the canopy is proportional to the available space for growth, which occurs in open stands and free from neighbourhood competition (Mutke et al., 2012). As trees get older, and its crown extend laterally, height growth drops slowly, but the tree continues to invest in stem diameter growth. From the mechanical stability standpoint, this is essential to support large crown, replace functionally inactive vessels and to support large fruit crops (Feldpausch et al., 2011). This prevents the tree from falling with its own weight. The slenderness index (h/d) clearly shows this effect, decreasing steeply with total aboveground biomass increment (Fig. 3c). The same pattern was found in Ilomaki et al. (2003) for silver birch, considering that this variable (slenderness) adds information about the competitive status and stability of the tree.

Hydraulic constraints may also be linked with tree height limits (Zaehle, 2005; Ryan et al., 2006), although presently there are no data to verify this hypothesis in Stone pine. The largest Portuguese trees from the sparser stand in Abegoaria (Table 1) have indeed lower height values. Comparing trees with similar biomass (Fig. 3b), the ones from Spain seem to grow taller than the Portuguese, which were in a more favourable site from the hydrological standpoint when comparing precipitation values between sites (Table 1). This contradicts the hydraulic constraints theory that reports lower heights for trees growing in water and nutrient depleted sites (Ryan and Yoder, 1997); however, Spanish trees were growing in dense conditions while the Portuguese were growing in very open stands (20–24 trees/ha). Thus, competition is probably more determinant in the morphological shape of the tree than possible hydraulic constrains.
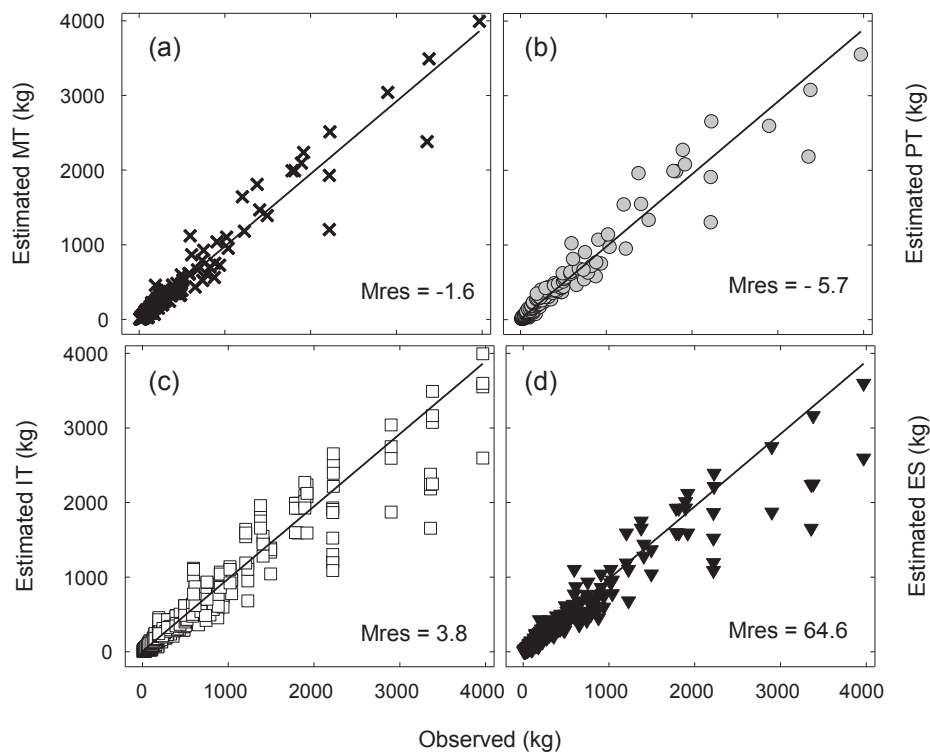
Fig. 8. Observed *versus* predicted total aboveground biomass, for each system of biomass equations: IT (Italy), PT (Portugal), SP (Spain) and MT (Mediterranean), applied to the Mediterranean dataset.
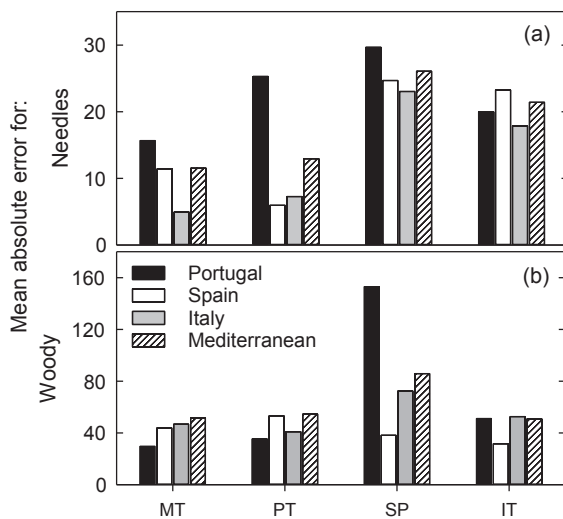

Fig. 9. Mean absolute error for each system of biomass equations (x-axis): IT (Italy), PT (Portugal), SP (Spain) and MT (Mediterranean) applied to each country dataset (bars) for the biomass components needles (a) and woody (b).

The root biomass showed a straightforward correlation with *d* irrespective of the location (Fig. 4e). Differences in soil type, quality and structure are expected to introduce some variability in the root system (Levy et al., 2004), leading the roots to develop preferably (or more prominently) at the surface or in depth. The stump and course roots right beneath the tree crown provides the primary structural fixation of the tree to the soil, therefore, it is expected to be correlated with the stem diameter supporting it. Major sources of uncertainty rely on the root development beyond the canopy perimeter. In Mediterranean soils, with hydromorphic characteristics, roots may extend far beyond the crown projection area and graft either within the same tree or between adjacent trees (David et al., 2013).

Leaves and stems are highly correlated biomechanically and physiologically (Fan et al., 2017). The ratio between autotrophic biomass (needles) and respiring biomass (woody biomass) in Stone pine shows a declining trend with stem diameter, similar to what has been observed in other studies e.g., (Naidu et al., 1998; Ilomaki et al., 2003; Mensah et al., 2016). As trees get older, more resources are allocated to the stem, branches and roots, which enables the tree to efficiently compete with neighbours, while ensuring mechanical stability (Poorter et al., 2015). Both heartwood formation and sapwood growth are carbohydrate sinks so the ratio of photosynthetic area should satisfy these carbon demands (Lotscher et al., 2004). In this study the decreasing pattern of auto to heterotrophic biomass is similar in all countries, although some Portuguese trees showed high needles-to-wood biomass ratio (Fig. 4e). This is consistent with Forrester et al. (2017) which shows that in open stands with low basal area there is less incentive for height/stem growth to outcompete with neighbours and more resources are available for foliage. These trees vegetate in mesic sites, so probably the access to environmental resources like water or nutrients allows a higher investment in the formation of new needles and in the maintenance of older needles cohorts. Moreover, the observed trend for lower needle-to-woody biomass ratio, although not statistically significant ($r^2 = 0.16$, $P > .05$), showed an increasing trend with site-specific aridity expressed by the P/2T (Precipitation divided two times the temperature) index (data not shown). This is in line with Poorter et al. (2015) study that showed a large reduction in leaf biomass when nutrients are the limiting factor. Thus, in mesic sites tress could retain more needle biomass. Accordingly, needles allometry in Stone pine seems to be plastic rather than fixed and highly influenced by environmental growing conditions during stand lifespan.

4.2. Added value on using biomass equations outside the range of the data used in its development

This study shows the importance of model diagnostics and cross-validation when selecting a biomass equation from the literature. The

ordinary nonlinear least squares method was selected to fit the biomass equations instead of a mixed model approach. In general, the random effects models were more biased and less precise.

As expected, the biomass prediction uncertainty is partially dependent on the sample dimension used for fitting, confirming that the models bias were higher for the largest trees (Fig. 5). This may be attributed to both the higher variability of larger trees and the difficulty of measuring them, compared with smaller ones (Sileshi, 2014). In the case of Stone pine, it is very important to have larger trees represented because the allometry changes considerably in mature stands, characterized by low tree densities and specific tree crown architectures. Within this study it was observed that Stone pine trees growing in open stands showed substantial changes in the aboveground biomass components partitioning. We observed less precision for the needles biomass component compared with the woody biomass components in the larger trees from the Portuguese dataset (Fig. 7).

The new developed stem biomass equations have a similar model efficiency, confirming that stem diameter has the highest correlation with the stem biomass (Fig. 4a). The model efficiency for the new needles component equation significantly increased (Table 3) when including the slenderness (h/d), in agreement with Correia et al. (2010). Regarding the published countries site-specific equations for branches (Table 2), only the stem diameter was included as independent variable. However, model efficiency significantly increased when total tree height was included in the new branches model (Table 3). For this component, the Spanish system (Ruiz-Peinado et al., 2011) provide different equations according with branches dimension while for the Italian system (Cutini et al., 2013) the branches are not separated from the stem component.

The diameter at breast height and total tree height were the most important variables explaining the variability of Stone pine. However, based on the statistics evaluation, it was observed that the MT-d and MT-dh do not differ greatly. Therefore, MT-d may be considered for its simplicity, since height is often unavailable and it is more challenging to measure with the same precision as diameter. António et al. (2007) argued that the inclusion of stand variables, together with tree variables, increases models performance. Also Forrester et al. (2017) considers that the inclusion of other independent variables such age, basal area, climate or latitude can reduce biomass variability estimates. However, Sileshi (2014) and also Kralicek et al. (2017) points that simple equations are easier to test and suffer less with statistics constraints, such as collinearity and do not substantially improve validation statistics over simpler formulations. The new developed system of aboveground biomass equations as well as the nonlinear root biomass equation fit these demands; they are simple and accurate for a wider range of tree diameter classes being especially recommended for biomass estimates in Mediterranean areas where biomass equations do not exist.

4.3. Lessons learned and extension of the results to other regions

The choice of biomass models to use in forest biomass and carbon fluxes quantification is an extremely important step and one of the most important sources of uncertainty in forest biomass estimates (Huy et al., 2016). An arbitrary choice of biomass equations from the literature leads to outputs easily manipulated by the user to fit its objectives. This poses serious threats to the integrity of forest biomass estimates in the future. Due to its simplicity, the use of biomass models application will continue to be widespread so care should be taken in interpreting and reporting results.

The results of this study highlights the importance of carefully examine the applicability of existing species-specific biomass to the data under evaluation. For example, neglecting the range of tree dimensions

used for model fitting resulted in biased estimates, particularly for high dimension trees. In this study, this was related with, not only, the high variability in component biomass allocation for high dimension tree between sites but also to the fact that these trees were less represented in biomass model original datasets. This means that, for biomass estimates of mature stands with high dimension trees, it is imperative a well representation of such dimension classes for biomass equations development.

Not always the country species-specific equations are the best. In this study we show how its application can be misleading taking the example of the PT equations developed with and without 35 high dimension trees. The range of tree dimensions used for biomass equations development, seems to overlap the possible regional edaphoclimatic conditions on tree growth.

This study did not take into account the effect of management due to lack of data for all the Spanish sites. As Stone pine has light demanding characteristics, we suspect that stand basal area or tree density could improve needles and branches biomass equations. However, field time and measurement costs increase greatly for collecting these stand variables . Unless it is proven that they add value and reduce considerably the final biomass estimates bias, we believe that simpler biomass equations will always be preferred.

Finally, we showed that the biomass estimates using the Mediterranean biomass equations developed using the three countries harvested trees provided lower biomass bias, irrespective of the country database. The new developed equations performed better than the regional ones and they are suitable for local or country biomass quantifications. The most important lesson learned in this study is that increasing the collaboration opportunities among data owners and users can lead to significant improvements in the existing models and therefore provide more accurate and feasible biomass estimates and, in that sense, both research and end-users win.

5. Conclusions

In this study, biomass allometric equations were developed for Stone pine, based on the largest existing dataset of harvested tree biomass data for the species and representative of its ecological and geographical Mediterranean distribution. The new developed Mediterranean system of biomass equations, allows estimating aboveground biomass more accurately through a wide range of diameter classes and across different sites. The study also included a new and more precise belowground biomass model due to the sharing of the existing data.

Future interesting work would be to address the topic of leaf area, canopy biomass partitioning and cone production under changing environment conditions. Particularly, biomass modelling for Stone pine should also focus on relating forest variables like tree biomass and volume, with canopy morphological variables especially the ones that can be traced by remote sensing tools like satellites, airborne laser scanning and UAV-based digital aerial photogrammetry.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.foreco.2018.07.037.

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