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Effects of Stand Structure on Stem and Crown Biomass

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Abstract

Above ground biomass can be divided in two broad classes, according to its potential use: stem biomass used mainly for timber; and crown biomass used either for bio energy or to maintain and improve ecosystem services, in particular stand and site sustainability and fertility. The aim of this study is to evaluate the differences and similarities of stem and crown biomass in forest stands as function of species, composition (pure *vs* mixed), structure (even-aged *vs* multiaged) and the stage of development (young *vs* adult). The analysis was carried out for eight species in 255 plots, in Portugal. The results revealed stem and crown biomass proportion depends on the tree species ecological characteristics, especially if trees are in free growth. Stem biomass proportion tends to be higher in stands managed for timber regardless composition or structure while crown biomass is higher in stands managed as agro forestry systems.

Keywords: Structure; Composition; Stage of development; Species; Statistical analysis

Abbreviations: Qr: Quercus Rotundifolia; Qs: Quercus Suber; Pp: Pinus Pinea; Ppi: Pinus Pinaster; Cs: Castanea Sativa; Qru: Quercus Rubra; Bc: Betula Celtiberica; PE: Pure Even-Aged; PM: Pure Multi Aged; ME: Mixed Even-Aged; MM: Mixed Multi Aged; QRS: Quercus Suber; SP: Mixed of Pinus Pinea; SPP: Pinus Pinaster; PCR: Quercus Robur; RRB: Betula Celtiberica

Introduction

From late 20th century onwards due to the need to evaluate carbon stocks, carbon sequestration and losses, as well as to estimate the biomass for energy, two main methods were used [1,2] the direct and the indirect. The indirect method, the most frequently used, is mathematical functions, with one or more dendrometric variables at tree level (diameter at breast height and total height) as explanatory variables. The functions are species and site-specific, due to the development behaviour of each species, which is also related with the site quality. This results in a wide number of functions [3-6]. Most of the allometric biomass functions per species are developed per component. While functions are always developed for stem, in which regards the other components some are developed for branches or leaves, whereas others aggregate the latter components in a class, the crown. Above-ground biomass is the sum of the biomass of all components. Thus due to their formulation it is possible to divide it in two broad classes; stem and crown. These classes can be related to of each component utilisation; stem for timber and crown either for bioenergy or to remain in the stand to maintain and/or improve the stand and site productivity. The maintenance of biomass in the forest stand, especially the crown components, is suggested in the frame of sustainability of the site, stand and productivity [7], especially in the poorer sites, due to the amounts of nutrients in the crown [8]. Inversely stems are poor in nutrients thus their removal has less impact on the overall productivity and sustainability of the system [9].

Stand structure dynamics are determined by the interactions between the individual trees in a stand, which are also result of composition (pure *vs* mixed), structure (even-aged *vs* multiaged), stage of development (young *vs* adult) and spatial arrangement, both horizontal and vertical. The species ecological characteristics, namely genetic features, epinastic control and shade tolerance are also of primordial importance in the stand structure dynamics [10]. As a result, above ground biomass as well as the stem and crown biomass are influenced by the aforementioned tree and stand characteristics.

The goal of this study is the evaluation of the effect of species and stand structure on the partitioning of above-ground biomass in two broad classes, stem and crown. The specific objectives are the analysis of species ecological characteristics, stand composition (pure *vs* mixed), structure (even-aged *vs* multiaged) and stage of development (young *vs* adult) on the proportion of stem and crown biomass.

Material and Methods

A set of 255 plots representative of the Portuguese forest area were selected (Table 1), to enable the characterisation of stem and crown biomass of different species and stand structures. In the field surveys, tree species were recorded and diameter at breast height, total height and height of the beginning of the crown were measured for all individuals with diameter at breast height larger than 5 cm [11]. Plots' composition (pure *vs* mixed) was evaluated with four criteria stand classification [12], and structure (even-aged *vs* multiaged) with diameter distributions using 2.5cm classes. Two stages of development were considered, evaluated visually in the field, young, pure even-aged plots (24 plots) and adult (231 plots). Many plots included young and adult trees, though in a small number in the even-aged plots and larger in the multiaged plots.

Table 1: Plots location, species and number.

Location	Central Coordinate	Species	Number
Mora	8°4'54''W, 38°51'16''N	Quercus rotundifolia	44
		Quercus suber	
Alcácer do Sal	8°40'28''W, 38°27'46''N	Quercus suber	88
		Pinus pinea	
Pinheiro da Cruz	38°16'56'' N, 8°45'19'' W	Pinus pinaster	40
Lousã	40°04'57'' N, 8°14'57'' W	Pinus pinaster	32
		Castanea sativa	
		Quercus robur	
Arcos de Valdevez	41°49'52'' N, 8°29'38'' W	Quercus robur	9
		Quercus rubra	
		Betula celtiberica	
Montargil	39°07'08'' N, 8°08'49'' W	Quercus suber	6
Extremoz	38°54'25'' N, 7°37'48'' W	Quercus suber	6
Chamusca	39°21'19'' N, 8°26'05'' W	Quercus suber	6
Coruche	39°06'27'' N, 8°21'48'' W	Quercus suber	24
		Pinus pinea	
		Pinus pinaster	

Stem and crown biomass were calculated with the allometric functions at tree level of Paulo and Tomé for *Quercus rotundifolia* and *Quercus suber*; of Correia et al. [13] for *Pinus pinea*; of IFN5 (2010) for *Pinus pinaster, Castanea sativa* and *Betula celtiberica*; of Carvalho [14] for *Quercus robur* and *Quercus rubra* and (Table 2). Other species than the aforementioned with a very small number of individuals were not considered in this analysis, as the inclusion could originate bias in the analysis [15]

Table 2: Stem and crown biomass allometric functions (where d is the diameter at breast height (in cm), h the total height (in m), c is the circumference at breast height $c=\Pi\times\frac{d}{100}$ (in m), *lc* the crown length (in m), *ww* stem biomass (in kg), *wc* crown biomass (in Kg)).

Species	Functions
Quercus rotundifplia	$ww = 0.164185\times d^{2.0011002}$
Quercus suber	$wc = 0.600169\times d^{1.355957} + 1.909152\times d^{1.200354}$
Pinus pinea	$ww = 18.85\times c^{1.68}\times h^{0.95}$
	$wbr = 0.0308\times d^{2.75761}\times\left(\frac{h}{d}\right)^{-0.39381} + 0.09980\times d^{1.39252}\times\left(\frac{h}{d}\right)^{0.71962}$
Pinus pinaster	$wc = 184.94\times c^{3.03} + 22.27\times c^{1.76}\times\left(\frac{h}{d}\right)^{-0.5} + 8.08\times c^{1.55}\times h^{0.47}$
	$ww = 0.0146\times d^{1.94687}\times h^{1.106577}$
Castanea sativa	$ww = 0.02.44\times d^{1.76603}\times h^{1.16402}$

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Betula celtiberica	$wc = 0.00440 \times d^2 \times h + 0.06574 \times d^{1.84096}$
Quercus robur	$ww = e^{\left(-3.323+\left(0.950\times\ln\left(d^2\times h\right)\right)\right)}$
Quercus rubra	$wc = e^{\left(-14.246+\left(2.248\times\ln\left(d^2\times h\right)\right)-0.01972\times\left(lc\times h\right)\right)}$

The stem and crown biomass was analysed considering species, structure and composition classes to enable further detail in the analysis. The species include *Quercus rotundifolia* (Qr), *Quercus suber* (Qs), *Pinus pinea* (Pp), *Pinus pinaster* (Ppi), *Castanea sativa* (Cs), *Quercus robur* (Qro), *Quercus rubra* (Qru), *Betula celtiberica* (Bc). The four structure classes are: *pure even-aged* (PE), *pure multiaged* (PM), *mixed even-aged* (ME) and *mixed multiaged* (MM); and the nine composition classes are: pure of *Quercus rotundifolia* (QR), pure of *Quercus suber* (QS), pure of *Pinus pinea* (PP), pure of *Pinus pinaster* (PPi), mixed of *Quercus rotundifolia* and *Quercus suber* (QRS), mixed of *Quercus suber* and *Pinus pinea* (SP), mixed of *Quercus suber, Pinus pinea* and *Pinus pinaste*r (SPP), mixed of *Pinus pinaster*, *Castanea sativa* and *Quercus robur* (PCR) and mixed of *Quercus robur*, *Quercus rubra* and *Betula celtiberica* (RRB). Considering species have different behaviours the analysis was done with stem and crown biomass as a percent of the above-ground biomass. The comparison between the abovementioned species and stand structure classes was done using non parametric Wilcoxon test, as variables did not meet the normality criteria, evaluated with Shapiro-Wilk or Kolmogorov-Smirnoff test, depending on the size of the sample, and implemented in R Development Core Team.

Results and Discussion

The stem and crown biomass proportion show a wide variability. It is derived, at least partially, from the differences between species (Table 3), decreasing in general from species managed as agro forestry systems (Qr, Qs and Pp) to those managed for timber (Cs, Qro, Qru, Be). This is probably related with the spatial arrangement of the trees. In the agro forestry systems stands have usually low density and trees are frequently isolated. However, the horizontal spatial distribution can be rather irregular with some trees isolated and others in clusters, which derives in a larger variability when compared with stands managed for timber where the horizontal spatial arrangement tends to be more regular. The proportion of stem biomass for adult trees is in average 64%, varying between 17% and 94%, with a coefficient of variation (CV) of 26%, while young trees is 63%, varying between 31% and 91%, with CV of 23%. The crown biomass for adult and young individuals has an average of 36% and 37%, CV of 47% and 38%, and ranges between 6% and 83%, and 9 and 70%, respectively. Noteworthy is the large variability of *Pinus pinaster*, which is a consequence of the different stand structures and stages of development. This species is present in pure, mixed, even-aged and multiaged the plots as well as young and adult plots. It is also noticeable for *Quercus suber* as they are present in young and adult plots and *Pinus pinea* as it is present in even-aged and multiaged plots (Table 3).

For all species crown biomass proportion when compared with stem biomass has a larger coefficient of variation (Table 3). Crown dimensions and consequently biomass are related to the species genetic characteristics, stage of development, epinastic control and shade tolerance. Different species have a wide range of crown shapes; *Quercus* spp., *Castanea sativa* and *Pinus pinea* have wide roundish branchy crowns, which are also related to their weak epinastic control. Inversely, *Pinus pinaster* and *Betula celtiberica* have narrow crowns and strong epinastic control [16,17]. The photo assimilates in young trees are primarily allocated to height growth while in adult trees are used predominantly for diameter growth, both stem and crown. Nevertheless, when available growing space is limiting, individual trees are not able to express their genetic characteristics due to the influence of the constellations of neighbours. Another determinant feature is the shade tolerance. Except for *Castanea sativa* and young *Quercus* spp., which show some shade tolerance, the other species and *Quercus* spp. adult individuals are shade intolerant [18-20], consequently stand structure and aerial growing space, determine their lateral development. Also, shading results in the death of the inferior part of the crown, especially in the shade intolerant species, reducing their length. The differences between species are corroborated by the significant differences among species by Wilcoxon test (*all*, p<0.05) Figure 1.

Table 3: Descriptive statistics of stem and crown biomass per species (where m is the mean, SD the standard deviation, min the minimum, max the maximum and CV the coefficient of variation).

Species	Stem Biomass					Crown Biomass				
	m	SD	min	max	CV	m	SD	min	max	CV
Qr	64.9	6	42.1	79	9.3	35.1	6	21	57.9	17.2
Qs	57.9	8.1	41.9	83.6	13.9	42.1	8.1	16.4	58.1	19.1
Pp	41.9	8	17.4	79.7	19	58.1	8	20.3	82.6	13.7

Ppi	77.5	8.7	30.5	94.1	11.2	22.5	8.7	5.9	69.5	38.4
Cs	83.4	2.3	77.1	90.9	2.7	16.6	2.3	9.1	22.9	13.8
Qro	82.8	2.7	78.6	91.3	3.3	17.2	2.7	8.7	21.4	15.7
Qru	80.4	1.2	78.2	86.8	1.5	19.6	1.2	13.2	21.8	6.1
Bc	81.1	1	78.6	83.9	1.3	18.9	1	16.1	21.4	5.5

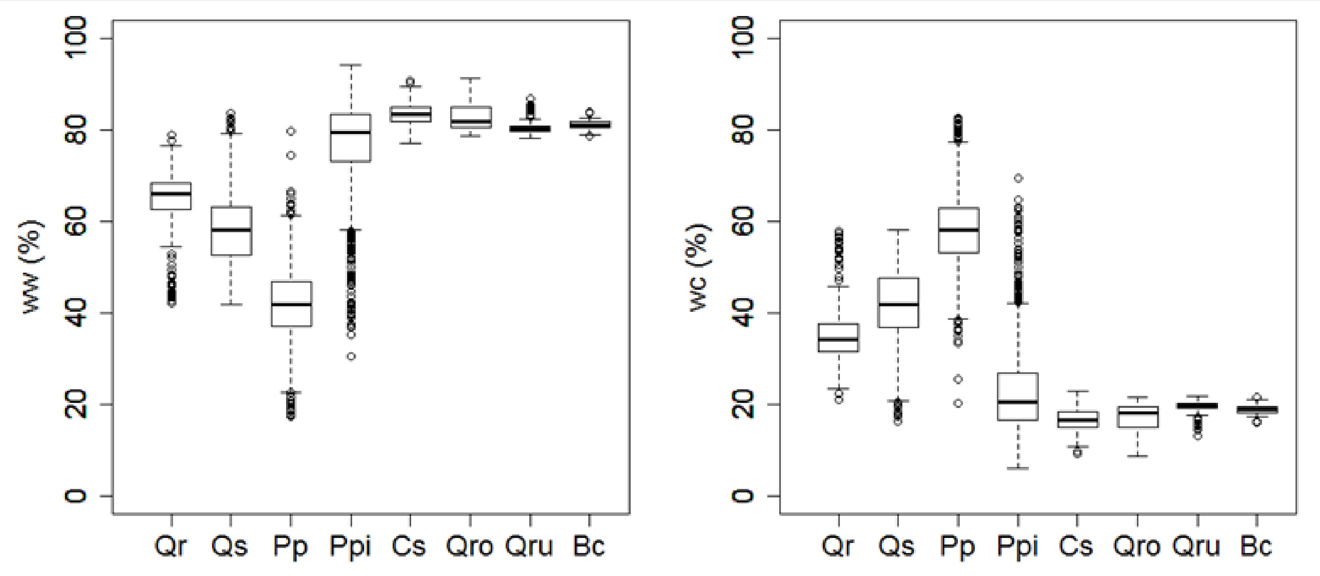

Figure 1: Boxplot of stem (ww) and crown (wc) biomass proportion per species.

The analysis per composition, structure and development stage classes of the plots show wider range for crown than for stem biomass proportion (Table 4). In general, variability of biomass increases from pure to mixed plots and from even-aged to multiaged plots, except for stem biomass that has a larger CV for pure than for mixed plots, reflecting the difference in the stage of development of the plots. When discriminating plots per structure classes (Figure 2a,c) variability increases from even-aged (PE, ME) to multiaged plots (PM, MM), explained by the number of species and their proportions per cohort [21]. PE plots dispersion is due to the stage of development of the plots. *Quercus suber* and *Pinus pinaster* have a similar number of young (10, 10 respectively) and adult (8, 11, respectively) plots. The smallest variability is found in the young plots were competition level is low and which have not or are in the early stages of the development of social classes, thus biomass partition being determined primarily by tree species characteristics. Conversely, adult stands where competition is stronger and social classes are already developed with some trees dominating others. These trends are also denoted by the significant differences between the structure classes (*all,* $p<0.05$), except between ME and MM for stem ($W=400, p=0.3$) and crown ($W=600, p=0.3$) biomass.

Table 4: Descriptive statistics of stem and crown biomass per composition, structure and development stage classes (where m is the mean, SD the standard deviation, min the minimum, max the maximum and CV the coefficient of variation).

Plot	Stem Biomass					Crown Biomass				
	m	SD	min	max	CV	m	SD	min	max	CV
Pure	58.2	14.3	28.4	84.8	25	41.8	14.3	15.2	71.6	34.2
Mixed	68.1	13.7	40.3	84.7	20	31.9	13.7	15.3	59.7	43
Even-aged	58.4	13.6	34.8	80.9	23	41.6	13.6	19.1	65.2	32.8
Multiaged	62.1	15.1	28.4	84.8	24	37.9	15.1	15.2	71.6	40
Adult	61.4	15.4	28.4	84.8	25	38.6	15.4	15.2	71.6	39.9
Young	57.6	5.5	49.9	70.6	9.6	42.4	5.5	29.4	50.1	13

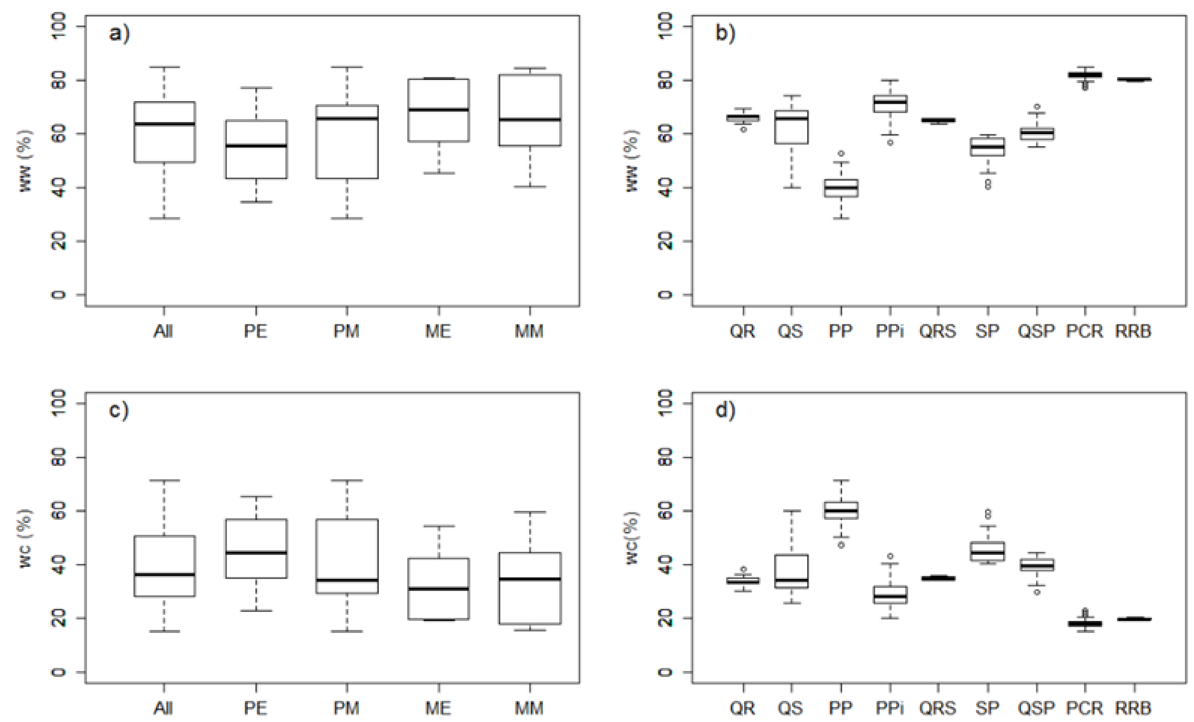

Figure 2: Boxplot of stem (ww) and crown (wc) biomass proportion for all plots, per structure classes (a,c) and per composition classes (b,d).

Further details can be attained when plots are analysed per composition classes. In general, stem biomass increases from agro forestry systems (QR, QS, PP, QRS, SP, SPP) to stands managed for timber (PPi, PCR, RRB), while the inverse is observed for crown biomass (Table 5 and Figure 2b,c). This is mainly due to stand management options. Agro forestry systems focus their management on bark and/or fruit production, thus promoting stem and crown diameter growth and trees with relatively short stems, frequently forked [22]. Contrariwise, in stands managed for timber the management focus is attaining a high straight stems, free of branches that optimise timber volume. The structure indices such as hd ratio, linear crown ratio and crown ratio [23,24] can bring some insights towards the understanding of the differences between the two stand types. Stands managed for timber when compared with agro forestry systems have higher hd ratio and crown ratio and lower linear crown ratio [25], in general resulting in a lower proportion of crown biomass in the former. These differences are corroborated by the significant differences of stem and crown biomass between the stands managed as agro forestry (QR, QS, PP, QRS, SP, SPP) and those managed for timber (PPi, PCR, RRB) (*all*, $p<0.05$). Yet, large variability is found for QS, PPi and PP. For the first two the dispersion can be explained by the development stages of the plots (young *vs* adult) and for the latter due to the proportion of species and individuals per cohort [24-31].

Table 5: Descriptive statistics of stem and crown biomass per composition class (where m is the mean, SD the standard deviation, min the minimum, max the maximum and CV the coefficient of variation).

Composition Class	Stem Biomass					Crown Biomass				
	m	SD	min	max	CV	m	SD	min	max	CV
QR	65.9	1.8	62	69.6	2.7	34.1	1.8	30.4	38.2	5.2
QS	62.9	7.5	40	74.5	12	37.1	7.5	25.5	59.9	20.3
PP	40.1	4.7	28	52.8	11.8	59.9	4.7	47.2	71.6	7.9
PPi	70.6	5.2	57	80	7.4	29.4	5.2	20	43.1	17.8
QRS	65	0.8	64	65.9	1.3	35	0.8	34.1	36.1	2.4
SP	53.8	5.4	40	59.7	10	46.2	5.4	40.3	59.7	11.6
SPP	61.1	5	55	70.3	8.2	38.9	5	29.7	44.7	12.8
PCR	82	1.8	77	84.8	2.2	18	1.8	15.2	22.8	10
RRB	80.3	0.5	80	80.9	0.6	19.7	0.5	19.1	20.5	2.3

Conclusion

Forest trees ecological characteristics determine the proportion of stem and crown biomass, particularly if they are in free growth. However, stand structure plays a key role on the above-ground biomass proportions. Composition, structure, stage of development and spatial arrangement, both horizontal and vertical, encompass a suite of interactions between individuals in a stand resulting in a wide range of variation of stem and crown biomass proportions per stand.

In general, crown biomass proportion is larger for species with wider crowns, weak epinastic control, shade tolerant and in free growth. At stand level crown biomass is larger for stands managed as agro forestry systems, especially those in the adult stage of development, while for stands managed for timber stem biomass proportion is larger. Overall stem biomass increases from pure to mixed, from even-aged to multiaged and from young to adult stands, while for crown biomass the opposite is observed.

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