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RESEARCH ARTICLE

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Biomass conversion and expansion factors in Douglas-fir stands of different planting density: variation according to individual growth and prediction equations

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Abstract

Aim of study: We built biomass expansion factors (BCEFs) from Douglas-fir felled trees planted with different planting densities to evaluate the differences according tree size and planting density.

Area of study: The Douglas-fir plantation under study is located on the northern coastal chain of Calabria (Tyrrhenian side) south Italy.

Materials and methods: We derived tree level BCEFs, relative to crown ($BCEF_c$), to stem ($BCEF_{st}$ = basic density, BD) and total above-ground ($BCEF_t$) from destructive measurements carried out in a Douglas-fir plantation where four study plots were selected according to different planting densities (from 833 to 2500 trees per hectare). The measured BCEFs were regressed against diameter at breast height and total height, planting density, site productivity (SP) and their interactions to test the variation of BCEFs. Analysis of variance (ANOVA) and the post hoc Tukey comparison test were used to test differences in $BCEF_t$, $BCEF_c$ and in BD between plots with different planting density.

Main results: BCEFs decreased with increasing total height and DBH, but large dispersion measures were obtained for any of the compartments in the analysis. An increasing trend with planting density was found for all the analyzed BCEFs, but together with planting density, BCEFs also resulted dependent upon site productivity. $BCEF_t$ average values ranged between 1.40 Mg m^{-3} in planting density with 833 trees/ha (PD833) to 2.09 Mg m^{-3} in planting density with 2500 trees/ha (PD2500), which are in the range of IPCC prescribed values for Douglas-fir trees.

Research highlights: Our results showed that the application of BCEF to estimate forest biomass in stands with different planting densities should explicitly account for the effect of planting density and site productivity.

Keywords: biomass; biomass expansion factor; planting density; *Pseudotsuga menziesii* (Mirb.) Franco.

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Introduction

International agreements like the United Nations Framework Convention on Climate Change (UNFCCC) and its Kyoto Protocol (1997) have recognized the potential of forests to mitigate the anthropogenic increase of atmospheric CO_2 concentrations, leading countries to give major attention to the quantification of the amount of carbon stored in the biomass. Under these agreements, countries are requested to estimate and report CO_2 emissions and removals of forest, and the credited sinks may be used as emission reductions (Somogyi *et al.*, 2006).

Biomass may be calculated from measured tree attributes using allometric equations (Zianis *et al.*, 2005; Coletta *et al.*, 2016), or calculated indirectly by multiplying the volume estimates by biomass factors that convert timber volumes to dry weight (density factor) and thereafter to whole tree biomass (expansion factor) (i.e. BCEF, biomass conversion expansion factor, Somogyi *et al.*, 2006; IPCC, 2006; Teobaldelli *et al.*, 2009). These factors are calculated as the ratio between the biomass of the compartment under consideration (e.g. aboveground; aboveground and roots) and the stem volume (s) of tree (s). The Good practice guidance for land use, land-use change and forestry (LULUCF, Penman *et al*., 2003) developed under the Kyoto protocol, lists BCEF approach as the preferred method for some of the tiers. Therefore national and regional aboveground biomass (AGB) estimates are generally calculated based on estimates of standing stem volume from forest inventories and from default biomass conversion and expansion factors (BCEFs). However, BCEF values can vary according to vegetation type, precipitation regime, mean annual temperature and tree age and size (e.g. Lehtonen *et al.*, 2004, Tobin & Nieuwenhuis, 2007, Petersson *et al.*, 2012), thus, use of default values for national- or regional-scale estimates might result in unreliable assessments of biomass, and carbon (Magalhães & Seifert, 2015). This is recognized by LULUCF guidance, since the higher tier methods call for greater specificity, such as country-level factors and factors specific to species.

In the present study we derived tree level BCEFs from destructive measurements carried out in a Douglas-fir plantation arranged in 4 different planting densities (from 833 to 2500 trees per hectare). The study allowed the evaluation of the planting density effects on the main stand dendrometric parameters through analysis of variation of the ratio of above-ground biomass to stem volume. The choice of the proper planting density is an extremely important factor, especially in wood plantations. Significant changes in planting density affect single tree and whole stand growth, which in turn affect yield potential and economic return. In Italy a BCEF value of 1.4 Mg m^{-3} for exotic conifer plantations C-reporting is suggested by the INFC (National Forest and Carbon Inventory, 2005). It was shown though that BCEF changes with age in Douglas-fir plantations in southern Italy (Marziliano *et al.*, 2015a), therefore using the constant value as reported by INFC leads to an underestimation of biomass for the younger stands and an overestimation of biomass for the older stands (Marziliano *et al.*, 2015b). In specific studies, prediction models for BCEFs have been proposed to better reflect stand characteristics comparatively to the use of a constant and unique (average value) for the species (e.g. Sanquetta *et al.*, 2011; Soares & Tomé, 2012; Enes Duque & Fonseca Fidalgo, 2014). The advantages of using locally derived biomass expansion factors are that while they compensate for regional environmental conditions (Schoene, 2002), they will also redress contemporary differences in growth patterns.

The objective of this research was to analyze the variation of total above-ground, crown and stem BCEFs in pure stands of Douglas-fir according to the planting density. We hypothesized that (i) the biomass expansion factors vary with stands characteristics and (ii) planting density could affect the value of the factors. BCEFs were calculated for every above-ground tree compartment (crown, stem and total) and different BCEFs for each planting density have been obtained. A regression analysis with the two major dendrometric parameters (diameter at breast height and total height) highlighted that dependencies of expansion factor on dendrometric characteristics are highly variable.

Materials and Methods

Study area

The Douglas-fir (*Pseudotsuga Menziesii*, (Mirb.) Franco) plantation under study is located on the northern

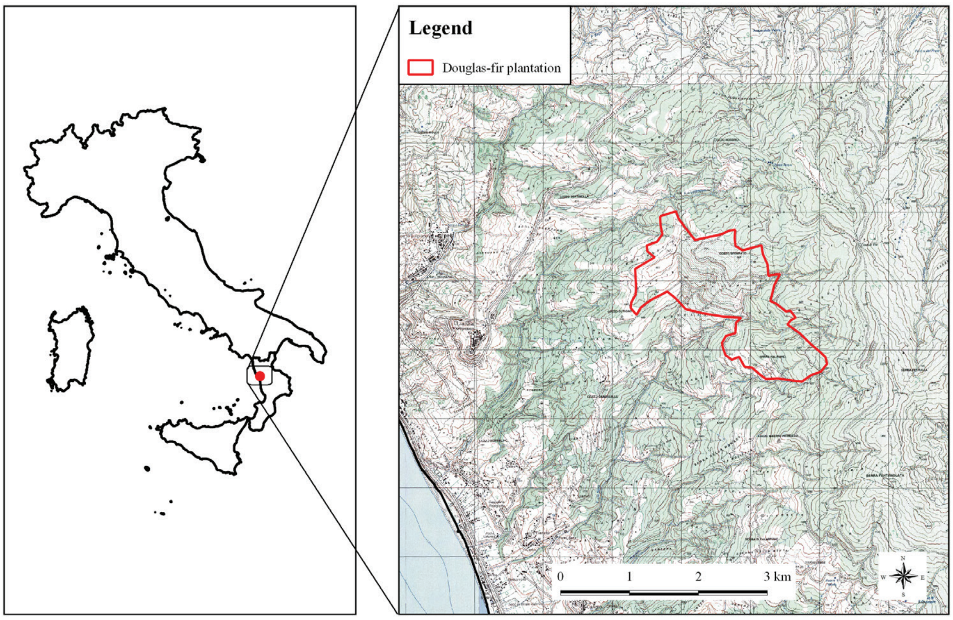

Figure 1. The map shows the location of the plots

coastal chain of Calabria, Tyrrhenian side of south Italy. The locality is called Serra Salinaro (39°, 25' N, 16°, 2' E), average altitude 900 m above sea level (Fig. 1). Regional Service of State Forest afforested the area in 1967 mainly with Douglas-fir. At the time of plantation (1967), Douglas-fir was planted with different planting densities (from 833 to 2500 trees per hectare). No silvicultural interventions were performed thereafter, and mortality is solely attributed to natural mortality. The climate of the area is typical Mediterranean. The annual rainfall is 1233 mm, with minimum precipitation in summer (88 mm) and a maximum during the winter (501 mm). Average annual temperature is 11.5 °C at an altitude of 950 m a.s.l. Average temperature of the coldest month is 3 °C, while the warmest has an average temperature of 20.8 °C. The problem of summer aridity is absent, owing to abundant precipitation, frequent fogs and exposure to moist air from the Tyrrhenian sea (Cantore & Iovino, 1989). Geologically the site is underlain by green and purple Paleozoic schist. According to FAO soils classification (FAO, 1998) soils are brown Podzols, with a plinthic horizon starting within 50 cm from the soil surface, deriving from basic metamorphic rocks, with highly decomposed organic material in more arid sites.

Data collection

The planting densities (PD) were: (i) PD2500 (2500 trees ha^{-1}); (ii) PD1667 (1667 trees ha^{-1}); (iii) PD1200 (1200 trees ha^{-1}); (iv) PD833 (833 trees ha^{-1}). When plantation was 15 years old, a randomized block design was used to test the effects of planting density. Totally, 12 permanent plots were established (4 treatments x 3 replicates). Plots had a square shape, with a surface area of 900 m^2. In order to avoid a "border effect" a 10 m buffer was left between contiguous plots. From this year and later on at age 25, 32 and 40, two orthogonal diameters at breast height (*DBH*) of all trees and the total height (*Ht*) of a representative sample (about 50%) of trees were measured in each plot (surveys at ages 32 and 40 have been used for other research studies).

When the plantation was 25 years old, the total height of 9 largest (diameter) trees (the 100 largest trees per hectare, according to Hägglund (1981)) was used to calculate the site productivity (SP) for each plot (Table 1). At the same age (25 years old), 35 trees were randomly selected for each planting density, according to the randomized block design (4 treatments x 3 replicates), but outside plots marked for dendrometric measurements (to avoid affecting tree-density). On the whole 420 selected trees were felled (stumps were cut at 20 cm height from soil) and divided into the following components: (1) stem; (2) branches; (3) needles; (4) crown (2 + 3); and (5) whole above-ground tree (1 + 4). Felled trees were scaled up to a 2.5 cm top diameter. The stem was defined as the length of the trunk from the stump to the height that corresponded to 2.5 cm diameter. The crown was divided into two sub-components: branches and foliage. Primary branches, originating from the stem, were classified in two categories: primary branches with diameters at the insertion point on the stem ≥ 2.5 cm were classified as large branches, and those with diameter < 2.5 cm were classified as fine branches.

The trees were cut from the stump and their heights were measured from breast height up to the height where diameter becomes 5 cm. Afterwards the stem was divided into sections, the first with 1.1 m length, the second with 1.7 m, and the remaining with 3 m, except the last, which length depended on the length of the stem. The volume of the highest part of each tree (where diameter was < 5 cm) was calculated using the cone's volume equation. The volumes of the stem were obtained by summing up the volumes of remaining sections calculated using Smalian's formula and the volume of the top. All the sections were weighted using a digital scale. Discs were removed at the bottom and top of the first section, and on the top of the remaining sections. The discs were dipped in drums filled with water, until constant weight (about 3 months), for its saturation and subsequent determination of the basic density, obtained by dividing the oven dry weight of the discs by the relevant saturated wood volume (calculated according to Archimedes' principle). Oven drying of all samples (of all the components) was done at 105°C to constant weight. Dry weights of each stem section were obtained by multiplying respective basic densities by relevant stem section volumes.

For what concerns crown, each sub-component (needles, large and fine branches) was weighted and

Table 1. Dendrometric characteristics and site productivity (SP). G = Basal area; Dg = Mean DBH; Ht = Total height; V= Volume; SP = Site productivity. Age of the trees = 25 years old

PD	N° trees ha^{-1}	Mortality	G (m^2 ha^{-1})	Dg (cm)	Ht (m)	V (m^3 ha^{-1})	SP (m)
2500	1634	35%	49.83	19.7	19.9	579.18	22.7
1667	1409	16%	51.53	21.6	21.4	628.94	23.4
1200	1056	16%	44.63	23.2	19.9	492.30	21.9
833	689	17%	41.24	27.6	19	410.99	20.7

from each a sample was taken to the laboratory for oven drying. Dry weight (biomass) of all the components of crown was estimated as the product of the fresh weight of a component and the ratio between the dry weight and the fresh weight of the sample.

Calculation of BCEF

The BCEF is a multiplier with dimension (Mg m^{-3}) that is used to convert timber volumes to dry weight (density factor) and thereafter to whole tree biomass (expansion factor) to estimate the biomass of whole tree. In this paper *V* refers to the stem volume with bark (m^3) and B_i to the biomass (dry weight, Mg) of the i compartment (total above-ground, stem and crown).

$$BCEF = \frac{B_i}{V} \quad \text{Eq.1}$$

BCEF relative to stem (corresponding to basic density, BD), to crown ($BCEF_c$) and to total above-ground biomass ($BCEF_t$) were calculated from sample trees belonging to different planting density. They were then regressed against DBH and height.

Stem volume and biomass of tree components were evaluated as described before.

Statistical analysis

Data from felled trees were used to analyze changes in BCEF varying with stand variables and to develop models to estimate BCEFs (of total above-ground, crown and stem). The Shapiro-Wilk test was performed to evaluate the normal distribution of data. Analysis of variance (ANOVA) and the post hoc Tukey comparison test were used to test differences in BCEFs between plots with different planting density. A 5% significance level was used throughout.

The effects influencing BCEFs accounted for the statistical analysis were DBH, height, planting density (PD), stand density at the age of 25 years old (SD_{25}), site productivity (SP) and their interactions.

As a preliminary analysis, these variables were scattered against each other to gain a general understanding of their behaviour. Afterwards, to estimate BCEF*i*, the variables were combined as in the following model:

$$Ln(BCEF_i) = b_0 + b_1 \cdot DBH + b_2 \cdot H + b_3 \cdot PD + b_4 \cdot SD_{25} + b_5 \cdot SP + b_n \cdot \text{interaction terms}_n \quad \text{Eq. 2}$$

The equation was built on the basis of the models proposed by Curtis (1967) and Clutter *et al*., (1983) and already adopted in a modified form by Marziliano *et al*.

Table 2. Descriptive statistics of the attributes measured on the sampled trees (age = 25 years old); the Shapiro-Wilk test shows that all attributes have a normal distribution. DBH Diameter at breast height, Ht total height, $BCEF_t$ (Total BCEF), $BCEF_c$ (Crown BCEF), BD (basic density of stem), SD standard deviation, SWT Shapiro-Wilk test (n=420)

PD (tree/ha)	Variable	Mean	SD	Skewness	Kurtosis	SWT Sig.
833	DBH (cm)	23.30	3.961	-0.338	0.129	0.080
	Ht (m)	18.50	1.037	0.521	-0.023	0.348
	$BCEF_t$ (Mg m^3)	1.40	0.191	0.596	0.303	0.367
	$BCEF_c$ (Mg m^3)	0.36	0.098	0.880	0.387	0.068
	BD (Mg m^3)	0.66	0.094	0.409	-0.325	0.570
1200	DBH (cm)	21.40	4.376	0.324	-0.789	0.392
	Ht (m)	19.36	1.802	-0.025	-0.267	0.733
	$BCEF_t$ (Mg m^3)	1.88	0.491	0.176	-0.586	0.784
	$BCEF_c$ (Mg m^3)	0.58	0.214	0.478	-0.006	0.535
	BD (Mg m^3)	0.71	0.123	0.913	0.059	0.051
1667	DBH (cm)	19.81	3.982	0.833	0.232	0.052
	Ht (m)	20.85	1.722	-0.197	-0.980	0.341
	$BCEF_t$ (Mg m^3)	1.55	0.340	0.710	-0.155	0.140
	$BCEF_c$ (Mg m^3)	0.48	0.173	0.723	-0.079	0.082
	BD (Mg m^3)	0.57	0.099	0.120	-0.170	0.887
2500	DBH (cm)	18.21	2.285	0.199	0.489	0.793
	Ht (m)	19.66	1.499	0.639	0.455	0.310
	$BCEF_t$ (Mg m^3)	2.09	0.535	0.660	-0.149	0.166
	$BCEF_c$ (Mg m^3)	0.63	0.224	0.944	0.633	0.073
	BD (Mg m^3)	0.81	0.184	0.073	-1.106	0.265

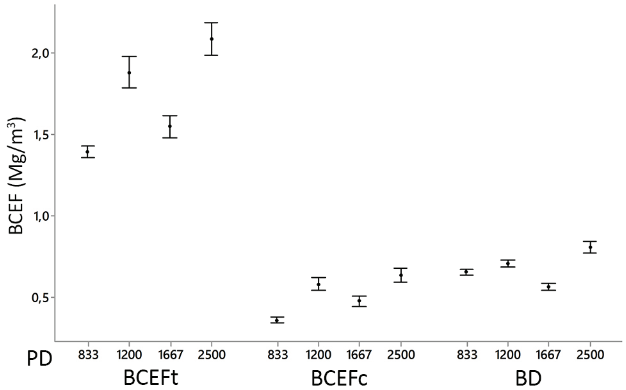

Figure 2. Mean +/- 2 standard errors of total above-ground ($BCEF_t$), stem (BD) and crown BEF ($BCEF_c$) (Mg m^{-3}) in the plots with different planting densities. Bars are 2 standard errors from mean.

(2013) and Marziliano *et al*. (2015c). The logarithmic transformation of the dependent variable produces a curve which, with the increase of the diameter, tends to be parallel to *x* axis, which is fully compatible to the biological growth of trees.

Candidate models were developed and the final model was selected on the basis of statistics criteria, considering the coefficient of determination (R^2) and the root mean square error (RMSE). The process involved a regression analysis with a stepwise procedure. Durbin Watson statistic was used to test the independence of residuals. VIF (variance inflation factor) was analyzed to check for multicollinearity.

Statistical analyses were made with R statistical software 2.3.0 (R development Core Team, 2008).

Results

The main descriptive statistics of the measured variables on the sampled trees (age = 25 years old), all with normal distribution, are summarized in Table 2. $BCEF_t$ average values ranged between 1.40 Mg m^{-3} (PD833) to 2.09 Mg m^{-3} (PD2500); $BCEF_c$ ranged from 0.36 Mg m^{-3} (PD833) to 0.63 Mg m^{-3} (PD2500) and BD varied from 0.57 Mg m^{-3} (PD1667) to 0.81 Mg m^{-3} (PD2500). The ANOVA showed significant differences between planting density for all the BCEFs ($BCEF_t$: $F_{(3/414)}$ =60.936; p=0.000; $BCEF_c$: $F_{(3/414)}$=46.063; p=0.000; BD: $F_{(3/414)}$=64.188; p=0.000), while no significant differences were found between replicates ($BCEF_t$: $F_{(2/414)}$ =0.508; p=0.602; $BCEF_c$: $F_{(2/414)}$=1.156; p=0.316; BD: $F_{(2/414)}$=0.083; p=0.920). Tukey test showed that $BCEF_t$ was significantly different between

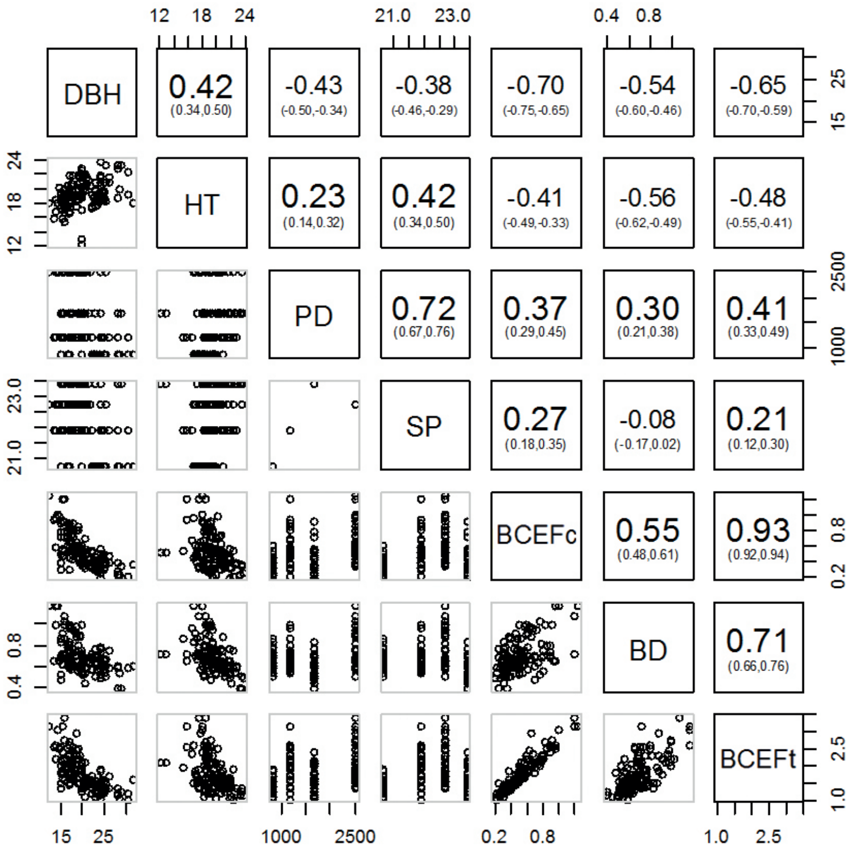

Figure 3. Scatterplot matrix (DBH = diameter at breast height; HT = Total height; PD = planting density; SP = site productivity; $BCEF_c$ = crown biomass expansion factor; BD = stem biomass expansion factor; $BCEF_t$ = total biomass expansion factor) with Pearson correlations and confidence interval, n=420.

all the PD. $BCEF_c$ had not significant differences between PD1200 and PD2500 but differences were significant between PD1667 and PD833. PD2500 and PD1667 had BD values statistically different from all the other PD (Fig. 2).

DBH, Ht, and PD were correlated with all BCEFs, instead SP was correlated only with $BCEF_t$ and $BCEF_c$; no correlation was found between SP and BD (Fig. 3). Large dispersion measures were obtained for any of the compartments in the analysis, especially for smaller trees (Fig. 3).

Starting from Eq. (2), after comparing different combinations and transformations of the variables through the stepwise procedure, the best fitting model was found to be the following:

$$Ln(BCEF_i) = b_0 + b_1 \cdot \frac{1}{DBH \cdot H} + b_2 \cdot PD + b_3 \cdot SP \quad \text{Eq. 3}$$

In no case the stand density at the age of 25 years old (SD_{25}) was significant, whereas planting density (PD) was significant for all the BCEFs. In the $BCEF_c$ equations, the SP did not appear to be significant ($P > 0.05$). As a result of this finding this variable was not included in the equation of $BCEF_c$. In general, all models provided a reasonable predictive power with R^2 values ranging from 0.57 (BD) to 0.69 ($BCEF_t$) (Table 3).

The strongest linear regression (R^2adj=69%; RMSE=0.158) was found for $BCEF_t$, with all variables as predictors. The variable formed by the combination of DBH and H could explain 66% of the total variance (Table 3), however, the PD and SP provided a further significant contribution in the estimate of $BCEF_t$. $BCEF_c$ was explained by the combination of DBH and H, and PD with a fitting of 65% (RMSE=0.253), with the first combined variable able to explain 64% of the total variance. BD was explained by all variables as predictor, with a fitting of 57% (RMSE=0.145). In the BCEFs estimates, values of Durbin Watson statistic ranged from 1.3 to 1.7. The variance inflation factor was always under 2 (for all the variance predictors used in the models), therefore absence of multicollinearity was corroborated (Zuur *et al.*, 2010).

Table 4 shows the final models with the estimated parameters and significance values for each model of BCEFs (p-values always < 0.001). The modeled relationship between all the BCEFs and DBH were plotted for all the planting densities (Fig. 4). BCEFs values decreased with increasing DBH, and were higher for higher planting density, with lower values for PD1667. For smaller DBH differences were higher and tended to disappear for larger DBH, for basic density this trend was less evident.

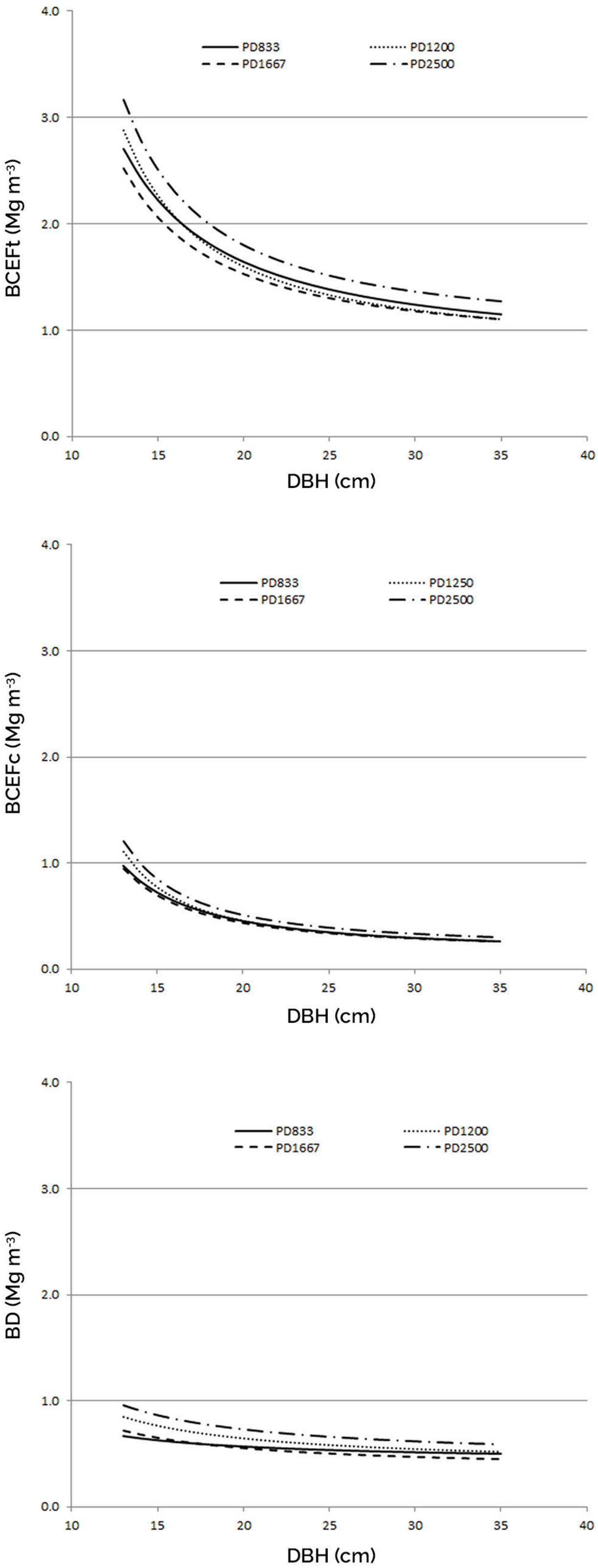

Figure 4. Total, crown and stem BCEFs (biomass expansion factor) models against DBH for the 4 planting densities (833 trees ha^{-1}; 1667 trees ha^{-1}; 1200 trees ha^{-1}; 2500 trees ha^{-1}).

Table 3. Model summary of stepwise regression in the estimate of BCEFs, derived by Eq. 2

	Step	Variable	R^2	R^2 Adj.	RMSE	Durbin-Watson
$BCEF_t$	1	1/DxH	0.657	0.656	0.166	
	2	PD	0.672	0.670	0.163	
	3	SP	0.690	0.687	0.158	1.307
$BCEF_c$	1	1/DxH	0.642	0.641	0.257	
	2	PD	0.654	0.652	0.253	1.391
BD	1	1/DxH	0.390	0.389	0.174	
	2	PD	0.439	0.436	0.167	
	3	SP	0.576	0.573	0.145	1.669

Discussion

Variation of BEFs with tree size

Total above-ground biomass expansion factor ranged from 1.4 to 2.1 Mg m^{-3} which are in the range of IPCC prescribed values for Douglas-fir trees (IPCC, Chapter IV, 2006). BCEFs values decreased with increasing DBH and tree height. Similar results have been observed in specific forest types, for example, aboveground BCEF for tropical forest (Brown *et al.*, 1989) and *Picea sitchensis* forest (Tobin & Nieuwenhuis, 2007) and total BCEF for *Chamaecyparis obtusa* forest and *Cryptomeria japonica* forest (Fukuda *et al.*, 2003).This trend is due to the changes in the biomass allocation as stands grow. While stem volume and stem biomass proportion in total tree biomass increase as the tree becomes larger, the other tree components decrease proportionally (Landsberg & Sands, 2011). Thus, larger and older trees have proportionally less foliage biomass as compared to smaller and younger ones. A decreasing trend in crown biomass across a range of tree ages (e.g. Kauppi *et al.*, 1995; Brown, 2002; Lehtonen *et al.*, 2004) may be explained by the physiological and competition attitudes of trees, since in the earlier growth phases they require greater photosynthetic biomass to win competition, whereas later, after canopy closure, shading of the tree crown, limitation of root expansion and natural pruning lead to a lower allocation into crown (Sanquetta *et al.*, 2011). The reverse dependence of BCEF on tree size is a result of an inverse relationship between wood density and tree size (Ducta *et al.,* 2010), since wood density slowly decreases as the trees grow older, even if it may increase again in older stands when the growth rate declines (Pajtík *et al.*, 2008).

Correlation between BCEF, DBH, H, SP and PD

The correlation matrix (Fig. 3) indicates that DBH is the variable more closely associated with crown and total BCEF, followed by height. This is in contrast with other authors findings (Levy *et al.*, 2010; Brown & Schroeder 1999; Lehtonen *et al.*, 2004) where it was shown that tree height had the greatest explanatory power in estimating BCEF. In our case only BD showed an higher dependence on H. As stated by Sanquetta *et al.* (2011) DBH can be chosen as explanatory variable, rather than height, because it is easier to measure, less time consuming and higher precision.

Table 4. Model equations for total ($BCEF_t$), crown (BCEFc) and stem (BD) with equation parameters, standard error of parameters (S.E.) and significance values (t and P)

Model equation		b_o	b_1	b_2	b_3
Total BCEF $Ln(BCEF_t) = b_0 + b_1 \cdot \frac{1}{DBH \cdot H} + b_2 \cdot PD + b_3 \cdot SP$	Parameter	0.354	265.281	0.00015	-0.35
	S.E.	0.229	10.950	0.00002	0.011
	t	3.350	27.043	6.581	-4.920
	Sig.	0.001	<0.0001	<0.0001	<0.0001
Crown BCEF $Ln(BCEF_c) = b_0 + b_1 \cdot \frac{1}{DBH \cdot H} + b_2 \cdot PD$	Parameter	-2.043	406.774	0.00015	
	S.E.	0.056	19.866	0.000	
	T	-36.662	20.476	7.125	
	Sig.	<0.0001	<0.0001	<0.0001	
Stem BD $Ln(BD) = b_0 + b_1 \cdot \frac{1}{DBH \cdot H} + b_2 \cdot PD + b_3 \cdot SP$	Parameter	1.737	196.694	0.00019	-0.133
	S.E.	0.210	11.074	0.00002	0.010
	T	8.272	17.761	11.620	-13.124
	Sig.	<0.0001	<0.0001	<0.0001	<0.0001

The lowest crown BEF was found in the less dense plot (PD833). An opposite trend was shown by Correia *et al.,* (2010). Our results seem in accordance with some authors findings (e.g. Ilomaki *et al.*, 2003), who refer that trees in conditions of poor competition tend to invest more in diameter growth instead of height growth. In PD1667 site productivity was the highest and this can explain the lower total and crown BCEFs than PD1200 and the absolute lowest BD, since better growing conditions led to a more rapid growth with larger tree rings width and then a lower basic density of wood. Our results are however in accordance with Kerr (2003), who found production of higher quality and quantity stem volume in higher planting densities of a plantation of *Fraxinus excelsior*, and Pfister *et al*., (2007) who found larger branch diameter of log in high density *Picea abies* stands.

Even if planting density alone had a low explanatory power in estimating BCEFs, its effect was significant and thus it ameliorated the variance explanation in total BCEF modelling. The same happened for site productivity. Conversely Antonio *et al.*, (2007) found no effect of planting density, site index or climate on tree allometry, whereas Black *et al.*, (2004) suggested that DBH, tree height and planting density should be used as inputs for biomass and BCEF models to reduce the error of estimate. Also Lehtonen *et al.,* (2004) showed that BCEF in Finland are affected by planting density, which can vary mainly due to varying forest management intensity. $BCEF_c$ and BD showed less the effect of PD and SP, or however other factors may be influencing allometry in the component together with these, and this effect is disguised when considering total BCEF. However when we modeled BCEFs considering the effect of planting density and site productivity we found significant differences among planting spacing due to density and DBH, with larger differences among close spacings and smaller differences among wide spacings (Fig. 4) in accordance with Harrington *et al.* (2009).

PD1667 showed the lowest BCEFs probably due to the highest site productivity, as also showed in studies carried out in spruce pine- and broadleaved-dominated stands in Norway, which gave lower BCEFs when the productivity in terms of site index increased (Viken, 2012).

Considering the variability of BCEFs with stand characteristics, if a constant BCEF is applied across all site productivity classes, even though the BCEFs are divided into age classes (Lehtonen *et al.*, 2004) or planting densities (Marziliano *et al.*, 2015a), the forest biomass of forest with low productivity can be underestimated, while the biomass of high productivity can be overestimated.

Conclusions

Regression of BCEFs against DBH and H showed a greater dispersion for smaller trees. Single default values are often used (UN-ECE/FAO, 2000; FAO, 2000; IPCC, 2006), but it is evident how these factors may vary, especially in young stands, depending on the species to be planted, growth phase, and site productivity. Therefore, calculations of BCEF under specific conditions shall be preferred.

Results from the regression analysis pointed out that the application of BCEF factors to estimate forest biomass in stands with different planting densities should explicitly account for the effect of planting density. Although this effect is expected to reduce as stand grows (Marziliano *et al.*, 2015a), during a period of non-disturbance, better estimates of biomass can be obtained when planting density is accounted for.

References

António N, Tomé M, Tomé J, Soares P, Fontes L, 2007. Effect of tree, stand, and site variables on the allometry of Eucalyptus globulus tree biomass. Can J Forest Res 37: 895-906. https://doi.org/10.1139/X06-276

Black K, Tobin B, Siaz G, Byrne KA, Osborne B, 2004. Allometric regressions for an improved estimate of biomass expansion factors for Ireland based on a Sitka spruce chronosequence. Irish Forestry 61(1): 50–65.

Brown S, 2002. Measuring carbon in forests: current status and future challenges, Environ Pollut 116: 363–372. https://doi.org/10.1016/S0269-7491(01)00212-3

Brown S, Gillespie AJR, Lugo AE, 1989. Biomass estimation methods for tropical forests with applications to forest inventory data. Forest Sci 35(4): 381–902.

Brown SL, Schroeder PE, 1999. Spatial patterns of aboveground production and mortality of woody biomass for Eastern US forests. Ecol Appl 9: 968-980.

Cantore V, Iovino F, 1989. Effetti dei diradamenti sull'umidità del suolo in popolamenti di douglasia della Catena Costiera (Calabria). Annali dell'Istituto Sperimentale per la Selvicoltura 20: 13-39.

Clutter JL, Fortson JC, Pienaar LV, Brister GH, Bailey RL, 1983. Timber Management: A Quantitative Approach. John Wiley & Sons, New York, USA.

Coletta V, Menguzzato G, Pellicone G, Veltri A, Marziliano PA, 2016. Effect of thinning on above-ground biomass accumulation in a Douglas-fir plantation in southern Italy. J For Res 27(6): 1313–1320. https://doi.org/10.1007/s11676-016-0247-9

Correia AC, Tomé M, Pacheco CA, Faias S, Dias AC, Freire J, Carvalho PO, Pereira JS, 2010. Biomass allometry and carbon factors for a Mediterranean pine (Pinus pinea L,) in Portugal. Forest Systems 19 (3): 418-433. https://doi.org/10.5424/fs/2010193-9082

Curtis RO, 1967. Height–diameter and height–diameter–age equation for secondgrowth Douglas-fir. Forest Sci 13 (4): 365–375.

Dutca I, Abrudan IV, Stancioiu PT, Blujdea V, 2010. Biomass conversion and expansion factors for young Norway spruce (Picea abies (L,) Karst,) trees planted on non-forest lands in Eastern Carpathians. Not Bot Hort Agrobot Cluj 38(3): 286–92.

Enes Duque T, Fonseca Fidalgo T, 2014. Biomass conversion and expansion factors are affected by thinning. Forest Systems 23(3): 438-447. https://doi.org/10.5424/fs/2014233-05128

Food and Agriculture Organization of the United Nations, 1998. World Reference Base for Soil Resources, Rome: FAO, ISRIC, ISSS [Soil Resource Report n. 84].

Food and Agriculture Organization of the United Nations, 2000. Global Forest Resource Assessment, FAO Forestry Paper 140, FAO. Rome, Italy.

Fukuda M, Iehara T, Matsumoto M, 2003. Carbon stock estimates for sugi and hinoki forests in Japan. Forest Ecol Manag 184: 1–16. https://doi.org/10.1016/S0378-1127(03)00146-4

Hägglund B, 1981. Evaluation of forest site productivity. Forestry Abstracts 42: 515–527.

Harrington TB, Harrington CA, DeBell DS, 2009. Effects of planting spacing and site quality on 25-year growth and mortality relationships of Douglas-fir (Pseudotsuga menziesii var, menziesii). Forest Ecol Manag 258: 18–25. https://doi.org/10.1016/j.foreco.2009.03.039

Ilomaki S, Nikinmaa E, Makela A, 2003. Crown rise due to competition drives biomass allocation in silver birch. Can J Forest Res 33: 2395-2404. https://doi.org/10.1139/x03-164

IPCC, 2006. Intergovernmental Panel on Climate Change, Guidelines for National Greenhouse Gas Inventories [http://www.ipcc.ch/].

Kauppi P, Tomppo E, Ferm A, 1995. C and N storage in living trees within Finland since 1950s, Plant soil 168-169: 633-638. https://doi.org/10.1007/BF00029377

Kerr G, 2003. Effects of spacing on the early growth of planted Fraxinus excelcior L. Can J Forest Res 33: 1196¬1207.

Landsberg JJ, Sands PJ, 2011. Physiological Ecology of Forest Production: Principles, Processes and Modelling. Oxford, UK: Elsevier Inc.

Lehtonen A, Mäkipää R, Heikkinen J, Sievänen R, Liski J, 2004. Biomass expansion factors (BEF) for Scots pine, Norway spruce and birch according to stand age for boreal forests. Forest Ecol Manag 188: 211–224. https://doi.org/10.1016/j.foreco.2003.07.008

Levy PE, Hale SE, Nicoli BC, 2010. Biomass expansion factors and root: shoot ratios for coniferous tree species in Great Britain. Forestry 77(5): 421-430. https://doi.org/10.1093/forestry/77.5.421

Magalhães TM, Seifert T, 2015. Estimation of tree biomass, carbon stocks, and error propagation in mecrusse woodlands. Open J Forestry 5: 471-488. https://doi.org/10.4236/ojf.2015.54041

Marziliano PA, Lafortezza R, Colangelo G, Davies C, Sanesi G, 2013. Structural diversity and height growth models in urban forest plantations: a case-study in northern Italy. Urban Forestry & Urban Greening, 12(2): 246–254. https://doi.org/10.1016/j.ufug.2013.01.006

Marziliano PA, Coletta V, Menguzzato G, Nicolaci A, Pellicone G, Veltri A, 2015a. Effects of planting density on the distribution of biomass in a Douglas-fir plantation in southern Italy. iForest 8: 368-376 [online 2014-09-09] URL: http://www.sisef.it/iforest/contents/?id=ifor1078-007.

Marziliano PA, Veltri A, Menguzzato G, Pellicone G, Coletta V, 2015b. A comparative study between "default method" and "stock change method" of Good Practice Guidance for Land Use, Land-Use Change and Forestry (IPCC, 2003) to evaluate carbon stock changes in forest. In: Atti del II Congresso Internazionale di Selvicoltura, Progettare il futuro per il settore forestale, Firenze, 26-29 novembre 2014, Accademia Italiana di Scienze Forestali, Firenze, Italy. Vol. 1, pp. 551-557.

Marziliano PA, Lafortezza R, Medicamento U, Lorusso L, Giannico V, Colangelo G, Sanesi G, 2015c. Estimating belowground biomass and root/shoot ratio of Phillyrea latifolia L. in the Mediterranean forest landscapes. Ann Forest Sci 72:585–593. https://doi.org/10.1007/s13595-015-0486-5

Pajtík J, Konopka B, Lukac M, 2008. Biomass functions and expansion factors in young Norway spruce (Picea abies [L.] Karst.) trees. Forest Ecol Manag 256: 1096–1103. https://doi.org/10.1016/j.foreco.2008.06.013

Penman J, Gytarsky M, Hiraishi T, Krug T, Kruger D, Pipatti R, Buendia L, Miwa K, Ngara T, Tanabe K, and Wagner F, 2003. Definitions and Methodological Options to Inventory Emissions from Direct Human-induced Degradation of Forests and Devegetation of Other Vegetation Types. The Institute for Global Environmental Strategies for the IPCC and The Intergovernmental Panel on Climate Change, Hayama, Kanagawa, Japan.

Petersson H, Holm S, Ståhl G, Alger D, Fridman J, Lethonen A, Lundstrøm A, Mäkipää R, 2012. Individual tree biomass functions or biomass expansion factors for assessment of carbon stock changes in living biomass – A comparative study. Forest Ecol Manag 270: 78–84. https://doi.org/10.1016/j.foreco.2012.01.004

Pfister O, Wallentin C, Nilsson U, Ekö PM, 2007. Effects of wide spacing and thinning strategies on wood quality in Norway spruce (Picea abies) stands in southern Sweden. Scand J For Res 22: 333– 343. https://doi.org/10.1080/02827580701504951

R Development Core Team, 2008. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.r-project.org/.

Sanquetta CR, Dalla Corte AP, Silva FS, 2011. Biomass expansion factor and root-to-shoot ratio for Pinus in Brazil. Carbon Balance Manag 6(6): 1–8. https://doi.org/10.1186/1750-0680-6-6

Schoene D, 2002. Terminology in assessing and reporting forest carbon change. In: Second expert meeting on harmonizing forest-related definitions for use by various stakeholders, FAO, Rome, Italy.

Soares P, Tome M, 2012. Biomass expansion factors for Eucalyptus globules stands in Portugal. Forest Systems 21(1): 141-152. https://doi.org/10.5424/fs/2112211-12086

Somogyi Z, Cienciala E, Mäkipää R, Muukkonen P, Lehtonen A, Weiss P, 2006. Indirect methods of large-scale forest biomass estimation. Eur J Forest Res 126 (2): 197-207. https://doi.org/10.1007/s10342-006-0125-7

Teobaldelli M, Somogyi Z, Migliavacca M, Usoltsev VA, 2009. Generalized functions of biomass expansion factors for conifers and broadleaved by stand age, growing stock and site index. Forest Ecol Manag 257(3): 1004–1013. https://doi.org/10.1016/j.foreco.2008.11.002

Tobin B, Nieuwenhuis M, 2007. Biomass expansion factors for Sitka spruce (Picea sitchensis (Bong) Carr,) in Ireland. Eur J Forest Res 126: 189-196. https://doi.org/10.1007/s10342-005-0105-3

UN-ECE/FAO, 2000. Forest Resources of Europe, CIS, North America, Australia, Japan and New Zealand (industrialized temperate/boreal countries). UNECE/ FAO Contribution to the Global Forest Resources Assessment 2000 Main Report United Nations, New York, Geneva.

United Nations Framework Convention on Climate Change – UNFCCC, 1997. Kyoto Protocol to the United Nations Framework Convention on Climate Change. FCCC/CP/L7/Add.1, 10 December 1997, UN. New York, USA.

Viken KO, 2012. Biomass equations and biomass expansion factors (BEFs) for pine (Pinus spp.), spruce (Picea spp.) and broadleaved dominated stands in Norway. Mastergradsoppgave ved Institutt for naturforvaltning, Universitetet for milijø- og biovitenskap 43 s. + vedlegg.

Zianis D, Muukkonen P, Ma¨kipa¨a¨ R, Mencuccini M. 2005. Biomass and stem volume equations for tree species in Europe. Silva Fennica Monographs N. 4, pp. 1–2, 5–63

Zuur AF, Ieno EN, Elphick CS, 2010. A protocol for data exploration to avoid common statistical problems. Methods Ecol Evol 1: 3–14. https://doi.org/10.1111/j.2041-210X.2009.00001.x