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Instituto Superior de Agronomia
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Analysis of Biomass Expansion Factors for the most important tree species in Portugal

Sónia Maria Marques Pacheco Faias

Dissertação para obtenção do Grau de Mestre em
Engenharia Florestal e dos Recursos Naturais

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Lisboa, 2009

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Em primeiro lugar agradeço à professora Margarida Tomé pelas suas excelentes capacidades científicas, pela sua paciência e dedicação por este projecto. Friso ainda que o facto de ter tido esta oportunidade de realizar este projecto me permitiu alcançar uma nova etapa na minha vida, o que não seria possível sem o seu contínuo incentivo.

Neste trabalho realço a utilização de dados de diferentes espécies florestais em Portugal, que foram partilhados entre diferentes pessoas e entidades, e atribuo os meus elogios a essa notável cooperação.

Todo e qualquer trabalho dentro de um grupo de investigadores, necessita de uma colaboração e, com certeza, de um apoio especial para a constante motivação que nem sempre é fácil de alcançar. Estes foram reconhecidos pelas minhas colegas e, fundamentalmente, pela minha família que soube compreender as longas horas que despendi neste projecto.

RESUMO

No presente trabalho são incluídos dois estudos, cujo contributo foi fornecer instrumentos para a quantificação de biomassa e de carbono na floresta portuguesa. Os dois estudos encontram-se ligados pela espécie florestal, Pinheiro bravo. No primeiro estudo foram ajustados dois sistemas de equações para a espécie pinheiro bravo, que permitem estimar ao nível da árvore a biomassa aérea e a biomassa por componente, cujo aplicação é geral para Portugal. Um dos sistemas de equações pode ser aplicado em povoamentos irregulares ou povoamentos regulares de idade desconhecida e o outro em povoamentos regulares de idade conhecida. Num segundo estudo, o objectivo principal foi comparar e analisar os resultados da aplicação de diferentes métodos para a estimação da biomassa do povoamento: i) pela aplicação das actuais equações de biomassa ao nível da árvore; ii) pela utilização de factores de expansão de biomassa publicados no relatório do Inventário Nacional de Emissões por Fontes e Remoções por Sumidouros de Poluentes Atmosféricos; iii) pelo ajustamento de equações para estimar factores de expansão de biomassa a partir de variáveis do povoamento facilmente obtidas com os dados de inventário florestal. Este segundo estudo foi desenvolvido para cinco das principais espécies florestais: pinheiro bravo, eucalipto, sobreiro, pinheiro manso e castanheiro.

Palavras chave: equações alométricas, sequestro de carbono, factores de expansão de biomassa

ABSTRACT

This study contains two working papers that are linked to a final objective: biomass and carbon estimates of Portuguese forests. The link is also established by one forest species, the Maritime pine. Two systems of compatible equations were developed in the first study for the maritime pine species, to estimate tree aboveground biomass and biomass per tree component at Portugal level. One of the systems may be applied to uneven aged stands or to even-aged stands in which the age is unknown and the other system can be applied to even-aged stands where age is known. The aim of the second study was to support a critical analysis comparing different methods to estimate stand biomass: i) applying the current tree level biomass equations; ii) using biomass expansion factors that have been published in the Portuguese National Inventory Report on greenhouse gases; iii) using models developed under this study, for the prediction of biomass expansion factors as a function of stand variables. This second study was developed for five of the main forest species in Portugal: maritime pine, eucalyptus, cork oak, umbrella pine and chestnut.

Keywords: allometric equations, carbon stocks, biomass expansion factors

RESUMO ALARGADO

No presente trabalho são incluídos dois estudos cuja ligação é a espécie florestal, Pinheiro bravo. A finalidade de ambos foi fornecer instrumentos para a quantificação de biomassa e de carbono na floresta portuguesa. O objectivo do primeiro estudo foi melhorar as equações existentes conferindo-lhes um carácter de aplicação geral para Portugal, agrupando os dados recolhidos em diferentes locais do país. Apresentam-se dois sistemas de equações para a espécie pinheiro bravo (*Pinus pinaster* Aiton), para estimar ao nível da árvore individual, a biomassa aérea e a biomassa para as principais componentes da árvore (lenho, casca, ramos e agulhas). Um dos sistemas de equações poderá ser aplicado em povoamentos irregulares ou povoamentos regulares de idade desconhecida e o outro em povoamentos regulares, cuja idade é conhecida. Os sistemas de equações foram obtidos por ajustamento simultâneo pelo método dos mínimos quadrados não lineares generalizados. Para a validação das equações seleccionadas foi aplicado o método Jack Knife, porque a grandeza da amostra não permitiu a separação em dois conjuntos, um para ajustamento e outro para validação. A selecção dos sistemas obtidos teve em consideração a melhor performance dos modelos e a inclusão de variáveis dendrométricas e variaveis do povoamento disponibilizadas pelo inventário florestal nacional. O segundo estudo teve como finalidade avaliar e quantificar o sequestro de carbono na floresta, resultante da aplicação de diferentes métodos de estimação da biomassa do povoamento. Para o efeito foram aplicadas as actuais equações de biomassa existentes para as principais espécies florestais portuguesas. Como método alternativo, foram aplicados os factores de expansão de biomassa, publicados no relatório do Inventário Nacional de Emissões por Fontes e Remoções por Sumidouros de Poluentes Atmosféricos por espécie, pela simples multiplicação destes valores constantes pelo volume do povoamento. A utilização de factores de expansão de biomassa, em relação à determinação da biomassa com recurso a equações alométricas da árvore, tem a vantagem de ser aplicável em dados já processados e em modelos de crescimento do povoamento que não incluem o módulo de biomassa. Com base na conclusão de diversos estudos de que o factor de expansão de biomassa não é constante ao longo do tempo, foram ajustadas equações para estimar factores de expansão de biomassa em função de variáveis do povoamento facilmente obtidas com os dados de inventário florestal. Estas equações foram utilizadas para estimar a biomassa do povoamento de algumas espécies florestais, nomeadamente: pinheiro bravo, eucalipto, sobreiro, pinheiro manso e castanheiro. Os resultados da sua aplicação são comparados com os resultados obtidos com os métodos anteriormente descritos.

INDICE

LISTA DE QUADROS

LISTA DE FIGURAS

ABREVIATURAS

NIF	National Forest Inventory
	Inventário Florestal Nacional
NIR	Portuguese National Inventory Report on greenhouse gases
	Inventário Nacional de Emissões por Fontes e Remoções por Sumidouros de Poluentes Atmosféricos (INERPA)
BEF	Biomass expansion factor
	Factor de expansão de biomassa
BEF*dt*	Biomass expansion factor including trees above the NFI diameter threshold
	Factor de expansão de biomassa incluindo árvores acima do diâmetro limite estipulado pelo IFN
ww	Stem wood tree biomass (kg)
	Biomassa do lenho da árvore (kg)
wb	Stem bark tree biomass (kg)
	Biomassa do casca da árvore (kg)
ws	Stem tree biomass (kg)
	Biomassa do tronco da árvore (kg)
wbr	Branches tree biomass (kg)
	Biomassa dos ramos da árvore (kg)
wl	Needles tree biomass (kg)
	Biomassa das folhas da árvore (kg)
wa	Aboveground tree biomass (kg)
	Biomassa acima do solo da árvore (kg)
d	Diameter at breast height (cm)
	Diâmetro à altura do peito (cm)
h	Total height (m)
	Altura total (m)
cl	Crown length (m)
	Profundidade de copa (m)
cr	Crown ratio
	Porporção de copa
t	Stand age (years)
	Idade do povoamento (anos)
dg/dug	Quadratic mean diameter / Quadratic mean diameter under bark (cm)
	Diâmetro quadrático médio / Diâmetro quadrático médio sem cortiça (cm)
hdom	Dominant height (m)
	Altura dominante (m)
N	Stand density (Number of trees ha^{-1})
	Densidade do povoamento (Numero de árvores ha^{-1})
G	Basal area (m^{2}ha^{-1})
	Área basal (m^{2}ha^{-1})
V	Stand volume (m^{3}ha^{-1})
	Volume do povoamento (m^{3}ha^{-1})
V*di*	Stand volume to a top diameter (m^{3}ha^{-1})
	Volume do povoamento considerando um diâmetro de desponta (m^{3}ha^{-1})
Wa	Stand biomass (Mg ha^{-1})
	Biomassa do povoamento (Mg ha^{-1})

I. INTRODUÇÃO

O presente trabalho resulta de dois estudos cujo contributo foi fornecer instrumentos para a quantificação de biomassa e de carbono na floresta portuguesa. Têm em comum uma espécie florestal, o Pinheiro bravo (*Pinus pinaster*), que representa 27% da floresta nacional (Tomé et al., 2007a).

A gestão florestal e as novas plantações são ferramentas reconhecidas como possíveis medidas que os países podem adoptar para fazer face à necessidade de redução de emissões de gases com efeito de estufa, referida no protocolo de Quioto (Lindner e Karjalainen, 2007). Neste contexto a estimação da biomassa da árvore e da biomassa do povoamento têm actualmente uma elevada importância, para a quantificação dos stocks de carbono na floresta. Mas a sua estimação directa é claramente muito dispendiosa, uma vez que implica amostragem destrutiva das árvores, o que realça a necessidade de utilizar métodos alternativos para quantificação da biomassa (de Wit et al., 2006).

No primeiro estudo, deste trabalho, pretende-se melhorar as equações existentes para a espécie pinheiro bravo (*Pinus pinaster* Aiton), cuja aplicação tem carácter local (e.g. Páscoa et al., 2004, Lopes, 2005). Assim, agrupou-se os dados recolhidos em diferentes locais do país, e adoptou-se a metodologia aplicada num estudo semelhante para o eucalipto (António et al., 2007). O objectivo é obter um sistema de equações, de aplicação geral ao país, para estimar ao nível da árvore a biomassa aérea e a biomassa para as principais componentes (lenho, casca, ramos e agulhas).

O objectivo principal deste trabalho reproduz-se no segundo estudo, através de uma análise crítica na aplicação de diferentes métodos para a estimação da biomassa do povoamento. Usualmente são utilizados dois métodos, aplicação de equações de biomassa ao nível da árvore, e aplicação de factores de expansão de biomassa (BEF) pela simples multiplicação destes valoers constantes pelo volume do povoamento.

Nos últimos anos foram desenvolvidas em Portugal equações alométricas para a predição da biomassa das seguintes espécies florestais: pinheiro bravo (*Pinus pinaster*) (Páscoa et al., 2004; Lopes, D., 2005), eucalipto (*Eucalyptus globulus*) (António et al., 2007), sobreiro (*Quercus suber) (*Tomé et al., 2007b), azinheira (*Quercus ilex)* (Paulo et al., 2003), carvalho negral (*Quercus pyrenaica*) (Carvalho, 2003), pinheiro manso (*Pinus pinea*) (Correia et al., 2008b) e castanheiro (*Castanea sativa*) (Patrício, 2004; Patrício et al., 2005). Em conjunto estas espécies representam 88% da floresta portuguesa (Tomé et al., 2007a).

Alguns autores, concluíram que o factor de expansão de biomassa não é constante ao longo do tempo, mas depende do estado de desenvolvimento do povoamento (e.g. Schroeder et al., 1997; Lehtonen et al., 2004; Soares e Tomé, 2004). Neste estudo pretende-se ajustar equações para estimar os factores de expansão de biomassa a partir de variáveis do povoamento facilmente obtidas com os dados de inventário florestal. A utilização de factores de expansão de biomassa, em relação à determinação da biomassa com recurso a equações alométricas da árvore, tem a vantagem de ser aplicável em dados já processados e em modelos de crescimento de povoamento que não incluam o módulo de biomassa.

Em resumo, o estudo irá incidir sobre a comparação de resultados obtidos na quantificação de stocks de carbono, utilizando os dados actuais de inventário florestal nacional, com os seguintes métodos de estimação de biomassa do povoamento: i) aplicação dos valores de BEF publicados no relatório nacional (Ferreira et al., 2008); ii) equações de biomassa ao nível da árvore; iii) modelos para a estimação de factores de expansão de biomassa ajustados em função de variáveis do povoamento.

O trabalho encontra-se estruturado em dois capítulos, onde cada um dos estudos é apresentado em formato de artigo, descrevendo dados, metodologia, resultados, discussão dos resultados, conclusões e referências bibliográficas.

A autora da presente tese, primeira autora dos estudos, foi responsável pela elaboração de ambos. No primeiro estudo os dados foram cedidos pelos co-autores. No segundo estudo os dados da espécie pinheiro bravo foram calculados de base pela autora e os dados das restantes espécies foram fornecidos pelos co-autores. A professora Margarida Tomé orientou ambos os trabalhos e o professor José Tomé orientou a análise estatística.

II. EQUATIONS TO ESTIMATE TREE BIOMASS IN *Pinus pinaster* AITON STANDS IN PORTUGAL

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Abstract

In this study two systems of compatible equations were developed for the maritime pine species, to estimate tree biomass and biomass per tree component at Portugal level. Biomass data by tree component (wood, bark, branches, and needles) were obtained by destructive sampling undertaken in several sites representing this species area in Portugal. Allometric equations were developed for each biomass component using as input tree variables that are usually measured in forest inventories. Total biomass of each tree was expressed as the sum of the tree biomass components. The effect of stand variables on the parameters of the models was also studied. Weighted regression was applied in order to account for the heterocedasticity associated with the nonlinear models selected. One of the systems may be applied to uneven aged stands or to even-aged stands in which the age is unknown and the other system can be applied to even-aged stands where age is known. Both systems of equations were fitted using nonlinear joint generalized least squares regression, also known as nonlinear iterated seemingly unrelated regression (ITSUR).

Keywords: allometric equations, tree biomass, maritime pine, seemingly unrelated regression

INTRODUCTION

The measurement of tree biomass has a considerable interest today and it separation by components is important when considering the impact of forest operations, such as thinning or pruning, in the ecosystem balance (Páscoa et al., 2004). Direct measurement of tree biomass is clearly a laborious and time-consuming process, this is the reason why tree biomass, both total and by component, are usually estimated with allometric equations (de Wit et al. 2006).

Maritime pine stands represent in Portugal 27% of the forest area according to data from the 2005-2006 national forest inventory (Tomé et al., 2007a).

There had been previous work on the development of tree biomass equations for the maritime pine species (e.g. Montero et al., 2005, Porté et al., 2002). In Portugal, such studies were based on small datasets and the equations may be used at local level (Páscoa et al., 2004, Lopes, 2005).

This study aim is to present an improved system of compatible equations to estimate tree aboveground biomass and biomass by tree component for the maritime pine species, using data sampled in different locations of Portugal. Allometric equations were developed for the most important tree components: wood, bark, branches and needles. Total biomass of each tree was expressed as the sum of those tree components.

The stand age can be a significant variable for tree allometry in even-aged stands (Porté et al., 2002; António et al., 2007), it also can be difficult or even impossible to obtain in forest inventories, namely in uneven-aged stands. Therefore, two systems of compatible equations are provided in this article, to estimate tree biomass in the maritime pine species in Portugal. One of them is including tree age among the input tree variables and the other does not include this variable. The other tree variables used as model predictors are usually measured in forest inventories, such as diameter at breast height (d) and total height (h).

DATA

Biomass data used to develop the systems of compatible equations were obtained by destructive sampling undertaken in several sites representing the maritime pine species area in Portugal. The different locals are shown in figure II-1 and describe next.

- A part of the data used came from Lopes (2005) where a total of 30 trees were sampled in stands located in North Portugal near Vila Real, with the goal to study net primary productivity of maritime pine in Portugal.
- A set of data came from Páscoa et al. (2004) where a total of 26 trees were sampled in the Leiria national forest. Another set of 26 trees came from several destructive samplings also made in the Leiria national forest, for a study on indicators of sustainable forest management (Tomé et al., 2007c).
- A total of 22 trees were sampled in three different locals at Portugal Center: Viseu, Lousã, Covilhã; for a study on forest monitoring in Europe with remote sensing (FMERS-II).
- A total of 11 trees were sampled in the south region of Portugal (Alcácer), for a study in carbon sequestration and sustainable management (Correia et al., 2008a).

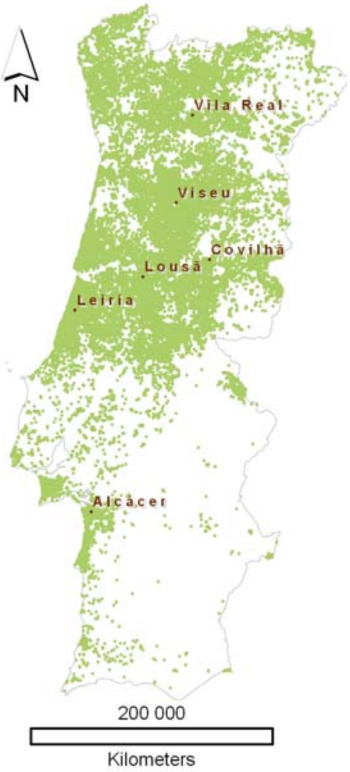

Figure II-1. Distribution of photo-plots (500 m grid) with maritime pine in Portugal (pure and dominant stands) and location of stands where the biomass data were collected

All the trees were sampled in even-aged stands, and the data included the following components: stem wood, stem bark, branches, leaves and total aboveground biomass. The trees from North Portugal were an exception, due to the fact that stem biomass was not split into their components: wood and bark. In some cases there was information on pine cones as well as on dead branches and needles from the last year of growth, but these components were not considered here. All authors have obtained fresh weight of every tree component in the field. The determination of the dry/fresh weight ratio implied in most cases stratification: stem was stratified by logs and a disk was removed from each one, and the crown was stratified into three layers. Each tree total aboveground biomass (wa) was expressed as the sum of their biomass components: stem (ws) or wood (ww) and bark (wb), branches (wbr) and needles (wl).

Several stand variables were computed for each one of the plots: stand age (t), stand density (N); stand basal area (G); dominant height (hdom); and stand volume (V), with the exception of the data set from North Portugal that had only stand age available. Table II-1 summarizes tree and stand variables in the dataset available for each site. Figure II-2 shows the relationship between the biomass of each tree component and tree diameter at breast height (d) or total tree height (h).

Table II-1. Characterization of the 115 trees used for the development of the biomass equations

Local	Nr. trees		d (cm)	h (m)	wa (kg)	t (years)	N (ha^{-1})	G (m^2ha^{-1})	hdom (m)
Alcacér	11	Min	9.1	11.7	34.5	55	200	19.7	21.8
		Mean	29.2	17.8	478.8	64	287	21.7	22.3
		Max	45.4	23.8	1189.8	75	360	23.5	22.8
Covilhã	3	Min	5.5	8.1	6.5	29	2222	43.7	12.7
		Mean	9.8	11.5	20.6	29	3667	53.3	14.0
		Max	20.4	14.3	77.8	29	3667	53.3	14.0
Leiria	52	Min	3.9	4.7	3.4	14	171	3.8	8.0
		Mean	26.2	16.4	397.8	46	499	21.7	17.1
		Max	67.5	32.5	1966.6	82	1600	33.1	27.9
Lousã	7	Min	5.5	7.8	18.8	25	2722	45.7	10.9
		Mean	12.3	10.5	94.3	25	3095	51.7	12.5
		Max	22.6	13.4	304.3	25	4444	57.9	15.3
Viseu	12	Min	9.6	13.0	22.9	37	610	31.9	16.7
		Mean	18.1	18.6	123.6	37	973	35.6	19.9
		Max	31.5	22.3	326.0	37	1448	38.3	22.2
Vale de Tâmega	30	Min	7.5	3.5	6.5	13			
		Mean	20.3	11.8	143.3	34			
		Max	35.7	22.2	489.1	54			

Symbols: t, stand age; N, stand density; G, stand basal area; hdom, dominant height; d, tree diameter at breast height; h, total tree height; wa, total tree aboveground biomass

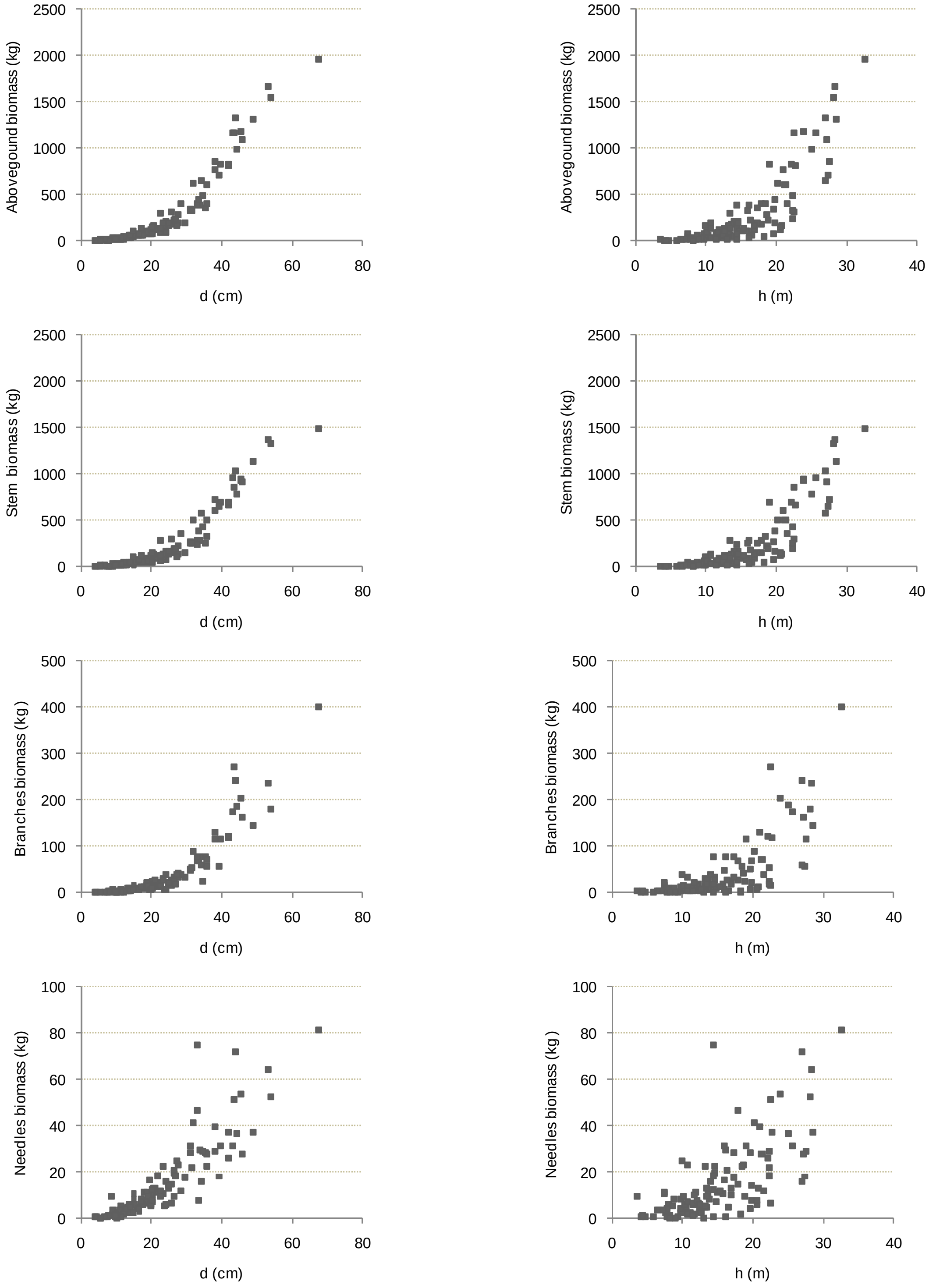

Figure II-2. Scatterplots of biomass of each tree component as a function of diameter at breast height (d) and total height (h)

METHODS

The allometric model

The most used equation to estimate tree biomass is the allometric model that relates the component of biomass (w) with tree variables. A common variable used as a single predictor is diameter at breast height (d) (e.g. Brown 2002; Landsberg and Waring 1997). Other authors (e.g. Reed and Tomé 1998; Monserud and Marshal 1999, António et al., 2007) have found a significant improvement on model fitting when tree height (h) is also used as a predictor. For crown components, some authors used crown length (cl) or crown ratio (cr) instead of total height (Carvalho and Parresol, 2003, António et al., 2007).

The allometric models considered in this study to model each biomass component were:

[1] $w = k\ d^{\alpha}$ (allometric model on d)

[2] $w = k\ d^{\alpha}\ x^{\beta}$ (allometric model on d and x)

where k, α and β are parameters, d is the tree diameter at breast height, w can be total aboveground biomass or biomass of one of the tree components considered in the study (stem, wood, bark, branches and needles) and x is a tree variable used as a predictor.

The final equations proposed to estimate tree biomass for the maritime pine species in Portugal were obtained throughout several analyses:

- Selection of an allometric model for each tree component: stem wood (ww), stem bark (wb), branches (wbr) and needles (wl).
- Improvement of the allometric model for each tree component by expressing the allometric constants as a function of stand variables.
- Simultaneous fitting of the systems of equations for each tree component and total aboveground biomass expressed as the sum of the tree components.
- Evaluation of two systems of equations, one is including stand age among the tree variables used as predictors and the other does not include this variable.

Selecting an allometric model for each tree component

As a first step the allometric models [1] and [2] were fitted to each tree component in order to select the most appropriate formulation. Model [2] was fit with x being total tree height (h), crown length (cl) or crown ratio (cr). All allometric models were initially fitted to each biomass component through nonlinear regression analysis using the PROC NLIN procedure of SAS 9.1 software (SAS Institute Inc., 2004). The performance of each one of the allometric model forms selected was evaluated using several criteria, most of them based on the press residuals (Myers, 1990):

1. $r_{pi} = \left(y_i - \hat{y}_{i,-i}\right)$ is the press residual for observation i, y_i is the observed value and $\hat{y}_{i,-i}$ is the predicted value for observation i when this observation has not been used for fitting the model

2. Model bias evaluated with the mean of the press residuals (***Mr$_{press}$***)

$$Mr_{PRESS} = \frac{\sum_{i=1}^{n} r_{pi}}{n}$$

3. Model precision evaluated with the mean of the absolute values of the press residuals (***Mar$_{press}$***)

$$Mar_{PRESS} = \frac{\sum_{i=1}^{n} \left|r_{pi}\right|}{n}$$

4. Percentiles 5 and 95 of the press residuals (***P5 and P95***)

5. Model efficiency

$$Ef = 1 - \frac{\sum_{i=1}^{n} r_{pi}{}^{2}}{\sum_{i=1}^{n} \left(y_i - \overline{y}\right)^2}$$

where $\overline{y}$ is the mean of the observed values.

6. Sum of squares of the press residuals

$$SSr_p = \sum_{i=1}^{n} r_{pi}^2$$

7. The regression assumptions were also checked:
    1. Normality of the studendized residuals assessed with normal QQ plots
    2. Homocedasticity assessed by visual analysis of the plot of studendized residuals over the predicted values.

Expressing the allometric constants as a function of stand variables

António et al. (2007) found a clear effect on the allometry of the trees with the stage of stand development. The technique proposed by these authors was considered in the goal of the present research, to improve the biomass allometric equations by expressing one of the parameters (*a*, *b* or *k*) as a function of one or more stand variables. This analysis was performed for each tree component using data from sites where stand variables were available (85 observations). The following steps were undertaken:

1. The allometric model was fitted with one of the parameters (*a*, *b* or *k*) changeable by stand, maintaining the other two parameters equal to their estimates obtained when fitting the model with the whole data set.

2. This procedure was repeated for the three parameters and the residual sum of squares (SSR) was compared in order to find out if one of them, when changing among sites, led to a higher reduction of SSR.

3. The relationship between site estimates for each parameter and stand variables (stand age, basal area, stand density and dominant height) was visually checked in order to select the parameter with a better relationship with a stand variable.

4. The stand-dependent allometric model was fitted using the whole data set, with the selected parameter expressed according to the better relationship found.

Homocedascity and normality of the model errors

In order to account for the heterocedasticity associated with the model errors, weighted regression was used to fit the selected model. Weights were found applying the methodology used by Parresol (2001), where the logarithm of squared residuals are expressed as a function of tree and stand variables. The all possible regressions algorithm from SAS software (SAS Institute Inc., 2004) was used to find the best models to express the logarithm of squared residuals. The most parsimonious model with a good fit and with all variables significantly different from zero was used as weight function. The non-normality of the errors was overcome with iteratively reweighted least squares regression using the Huber function to reduce the influence of data points containing large errors on the fit (Myers, 1990). These steps are considered important in the final models in order to assurance the reliability of the statistical tests used and to assess the significance of the parameters expressing the relationship between the allometric constants and the stand variables.

Simultaneous fitting

The models selected for each tree component as well as total aboveground tree biomass, were fitted using nonlinear joint generalized least squares regression, using the option ITSUR from the PROC MODEL procedure of SAS software (SAS Institute Inc., 2004), namely known as nonlinear iterated seemingly unrelated regression. During the simultaneous fitting the weights also calculated with the Huber function were taken from the individual fitting of each tree biomass component. Weights for the total tree biomass equation were found by individual fitting of an equation for this variable.

Total aboveground biomass of each tree was expressed in the system as the sum of their tree components. The stem biomass components, wood and bark were not available on the trees sampled in North Portugal, where an aggregate value for stem biomass was measured. In order to overcome this problem and still take advantage of all the information available, the biomass of these tree components were consider equal to zero and the equations were written as follow:

$$\begin{cases} ww = k_w d^{\alpha w} \; x^{\beta w} \; \theta_w \\ wb = k_b d^{\alpha b} \; x^{\beta b} \; \theta_b \\ wbr = k_{br} d^{\alpha br} \; x^{\beta br} \\ wl = k_l \, d^{\alpha l} \; x^{\beta l} \\ ws = k_w d^{\alpha w} \; x^{\beta w} + k_b d^{\alpha b} \; x^{\beta b} \\ wa = k_w d^{\alpha w} \; x^{\beta w} + k_b d^{\alpha b} \; x^{\beta b} + k_{br} d^{\alpha br} \; x^{\beta br} + k_l \, d^{\alpha l} \; x^{\beta l} \end{cases}$$

where *d* is the tree diameter at breast height (cm), *x* can be h as the tree total height (m), *cl* as the crown lenght (m) or *cr* as the crown ratio, α_i and β_i are allometric parameters, θ_i is a dummy variable that takes values 1 when variable *i* had been measure and 0 if it did not been measure, *ws* is the stem biomass tree component (kg), *ww* is the wood biomass tree component (kg), *wb* is the bark biomass tree component (kg), *wbr* is the branches biomass tree component (kg), *wl* is the needles biomass tree component (kg) and *wa* is the total aboveground tree biomass (kg). This way trees sampled in the North Portugal were taken into account for the fitting of the stem biomass, but not for the stem wood biomass and stem bark biomass.

Evaluation of the systems

No independent data set was available to evaluate the system of equations developed. Therefore a re-sampling procedure was used in order to evaluate the predictive ability of the system. The Jack Knife method was applied, leaving out each tree once. The system of equations was refitted 115 times, excluding from each run a tree, randomly sampled from the 115 trees used in the study. Independent prediction residuals (observed-predicted), similar to press residuals, were obtained in each run with the observations that had been left out from the fitting. Evaluation was based on the above described statistics for the press residuals.

RESULTS

Selection of allometric models for each tree component

Table II-2 shows the results of the different forms of the models fitted in the first stage. Models that used an additional predictor resulted in smaller residual sums of squares of press residuals (SSrp) than those obtained for the corresponding model based only on diameter at breast height. The selection of the allometric formulation to be used for further analysis was based on this results.

Table II-2. Comparison of models using only diameter [1] with those using diameter and height or crown length [2a, 2b] and age [3]

Tree component	Variables in the model		Mr$_{PRESS}$	Mar$_{PRESS}$	P5	P95	SSrp	Ef
Wood	[1]	d	-22,8435	81,1282	-262,5520	180,2240	3213290	0,8408
	[2a]	d,h	-15,4423	46,0269	-90,2382	122,4490	1285015	0,9440
	[3]	d,h,t	-7,4426	33,8902	-76,9044	92,5634	722264	0,9689
Bark	[1]	d	-1,7473	8,3284	-17,3612	22,0157	42483	0,8288
	[2a]	d,h	no improvement in relation to model [1]					
	[3]	d,t	-1,1975	7,6193	-21,0732	18,4748	34681	0,8526
Stem	[1]	d	-18,8958	67,9153	-146,5220	174,1960	2128889	0,9159
	[2a]	d,h	-17,3423	57,5042	-90,1068	187,2270	1654276	0,9369
	[3]	d,h,t	-9,1097	43,3648	-84,9435	129,7800	968215	0,9637
Branches	[1]	d	-2,4346	11,4799	-28,5152	31,8272	61476	0,8927
	[2a]	d,h	no improvement in relation to model [1]					
	[2b]	d,cl	-2,5747	11,5278	-22,8822	25,1512	62064	0,8939
Needles	[1]	d	-0,3324	4,8183	-10,9927	10,5401	7609	0,7679
	[2a]	d,h	-0,2693	4,7524	-11,9177	9,1077	7274	0,7936
	[2b]	d,cl	no improvement in relation to model [1]					
Aboveground	[1]	d	-23,0218	80,9026	-159,1160	204,6750	3597516	0,9208
	[2a]	d,h	-20,0336	73,9697	-148,5660	189,1840	2907147	0,9373
	[3]	d,h,t	-6,7564	58,3646	-159,6980	129,2370	1693586	0,9601

Expressing the allometric constants as a function of stand variables

Figure II-3 shows an example of the relationships found between the parameter estimates and stand variables – stand age (t) and dominant height (hdom), for the stem component. No relationship was found for any other tree component or other stand variables. Stand age appears as the stand variable that better explains the inter-stand variation of the allometric constants. In Table II-2 it is possible to compare model [3] that includes stand age in the parameter *k*, with the models that do not include stand variables.

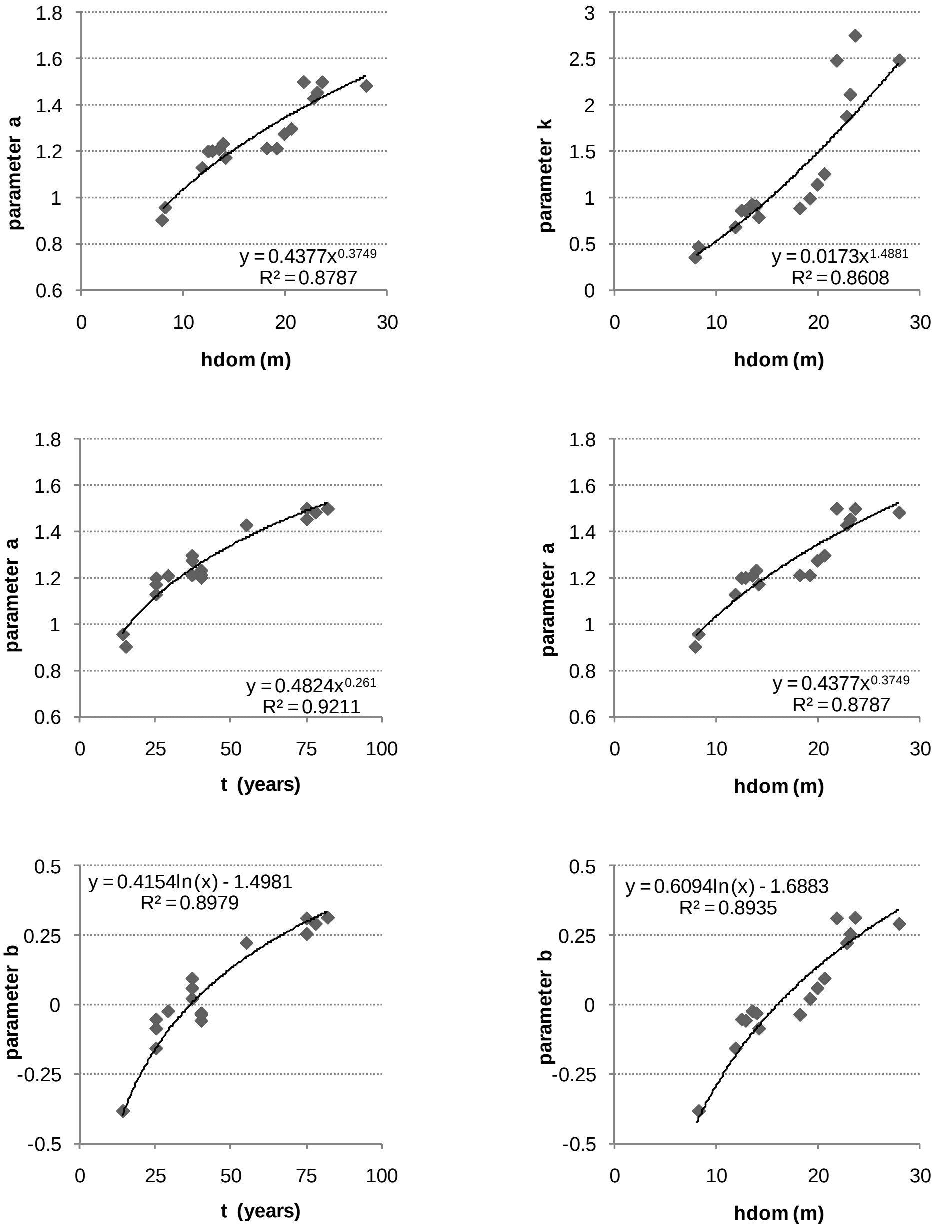

Figure II-3. Scatter plots of the estimates of a, b and k parameters of the nonlinear allometric model for the stem wood component with stand variables: age and dominant height

Individual fitting

Table II-3 presents the individual models selected. Stand age was the stand variable that most reduced the residual sum of squares in the stem components (wood and bark) and total aboveground biomass. Thus two models are presented for those components, one with stand age as regressor and the other without this variable.

Table II-3 Final models selected for each component with parameters independently estimated and their correspondent modelling efficiency (n=115)

Tree component	Equation	Ef
Wood	$\boldsymbol{ww} = (0.0066\ \boldsymbol{t}^{0.6314})\ \boldsymbol{d}^{1.8444}\ \boldsymbol{h}^{0.5968}$	0.9422
	$\boldsymbol{ww} = 0.0120\ \boldsymbol{d}^{1.9771}\ \boldsymbol{h}^{1.0923}$	0.8978
Bark	$\boldsymbol{wb} = (0.0090\ \boldsymbol{t}^{0.4979})\ \boldsymbol{d}^{1.8631}$	0.8353
	$\boldsymbol{wb} = 0.0144\ \boldsymbol{d}^{2.2929}$	0.8012
Branches	$\boldsymbol{wbr} = 0.00384\ \boldsymbol{d}^{2.7820}$	0.8642
Needles	$\boldsymbol{wl} = 0.0637\ \boldsymbol{d}^{1.5950} \left(\boldsymbol{h} / \boldsymbol{d} \right)^{-0.6758}$	0.7881
Stem	$\boldsymbol{ws} = (0.0089\ \boldsymbol{t}^{0.5843})\ \boldsymbol{d}^{1.8813}\ \boldsymbol{h}^{0.5621}$	0.9256
	$\boldsymbol{ws} = 0.0134\ \boldsymbol{d}^{2.0020}\ \boldsymbol{h}^{1.0698}$	0.8760
Aboveground	$\boldsymbol{wa} = (0.0125\ \boldsymbol{t}^{0.4209})\ \boldsymbol{d}^{2.1261}\ \boldsymbol{h}^{0.4759}$	0.9381
	$\boldsymbol{wa} = 0.0228\ \boldsymbol{d}^{2.1509}\ \boldsymbol{h}^{0.8117}$	0.9216

Simultaneous fitting

Tables II-4 and II-5 show the two systems of equations for tree biomass estimates for the maritime pine species in Portugal. The first table only considers tree variables as predictors: total height and diameter at breast height. The second table includes, in addition to those tree variables the stand age. The convergence was easily obtained for both systems.

Table II-4. Final models selected for each component with parameters simultaneously estimated through ITSUR with parameters common for stands of different age(n=115)

Tree component	Equation	Ef.(r2aj)
Wood	$\boldsymbol{ww} = 0.011565\ \boldsymbol{d}^{1.868252}\ \boldsymbol{h}^{1.216072}$	0.9159
Bark	$\boldsymbol{wb} = 0.015953\ \boldsymbol{d}^{2.274024}$	0.8032
Branches	$\boldsymbol{wbr} = 0.003971\ \boldsymbol{d}^{2.763628}$	0.8869
Needles	$\boldsymbol{wl} = 0.065631\ \boldsymbol{d}^{1.612475} \left(\boldsymbol{h} / \boldsymbol{d} \right)^{-0.547370}$	0.7908
Stem	$\boldsymbol{ws} = \boldsymbol{ww} + \boldsymbol{wb}$	0.9077
Aboveground	$\boldsymbol{wa} = \boldsymbol{ww} + \boldsymbol{wb} + \boldsymbol{wbr} + \boldsymbol{wl}$	0.9171

Table II-5 Final models selected for each component with parameters simultaneously estimated through ITSUR and with parameters expressed as function of age (n=115)

Tree component	Equation	Ef.(r2aj)
Wood	$\boldsymbol{ww} = (0.006249\ \boldsymbol{t}^{0.408223})\ \boldsymbol{d}^{1.805945}\ \boldsymbol{h}^{0.945397}$	0.9332
Bark	$\boldsymbol{wb} = (0.008\ \boldsymbol{t}^{0.358303})\ \boldsymbol{d}^{2.081983}$	0.7813
Branches	$\boldsymbol{wbr} = 0.003372\ \boldsymbol{d}^{2.807565}$	0.8846
Needles	$\boldsymbol{wl} = 0.061843\ \boldsymbol{d}^{1.618916}\ \left(\boldsymbol{h}/\boldsymbol{d}\right)^{-0.57473}$	0.7888
Stem	$\boldsymbol{ws} = \boldsymbol{ww} + \boldsymbol{wb}$	0.9234
Aboveground	$\boldsymbol{wa} = \boldsymbol{ww} + \boldsymbol{wb} + \boldsymbol{wbr} + \boldsymbol{wl}$	0.9344

Evaluation of the systems

Figure II-4 shows for each compatible system fitted (with and without parameters depending on stand age), the plot of total aboveground biomass observed and estimated for each tree left out in each run using the Jack Knife method. The values for the considered statistics are shown in table II-6.

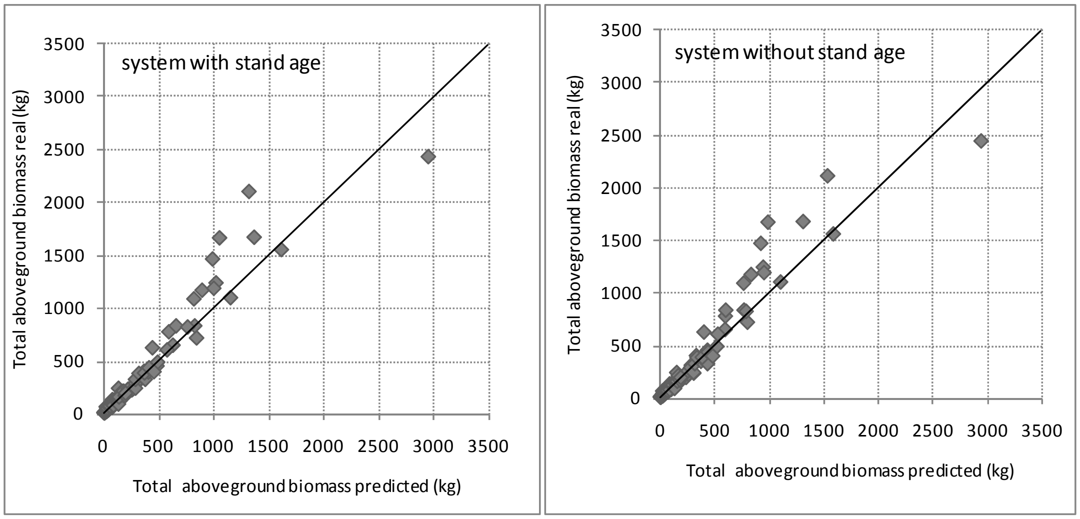

Figure II-4 Total aboveground biomass observed and predicted

Table II-6 Statistics for the predicted residuals calculated using Jack Knife method for each compatible system

Total aboveground biomass system	$\mathbf{m_{rpress}}$	$\mathbf{m_{arpress}}$	**p5**	**p95**
without stand age	30.076	54.852	-50.399	301.125
with stand age	30.106	52.802	-48.186	235.321

DISCUSSION

Diameter at breast height is one of the most commonly used predictors of tree biomass because it shows a high correlation with all the tree biomass components and it is a variable easily measured in the field with high accuracy. In the present analysis the use of total height as an additional predictor revealed a significant increase in the predictive ability of the models, with the exception for the bark and the branches components. António et al. (2007) found similar results for eucalyptus. Crown length was a significant predictor for the branches biomass component, but it was not included in the final model fitting, because the increase in predictive ability was small and it represents an additional variable to be measured in the field or to be estimated with a prediction error.

Porté et al. (2002) found, in the study developed for *Pinus pinaster* in Aquitaine, that stand age greatly improved the prediction ability of the branches and stem models. In this study the stand age was also significant when expressed in the parameters for the total aboveground biomass and stem tree components (wood and bark), namely in the k parameter. The stand age was in addition to total height and diameter at breast height included in one of the presented systems. Stand age is a variable that is frequently not available and that does not make sense in uneven-aged stands. Therefore a second compatible system was obtained excluding it from the input variables of the models.

When the size of the sample does not allow the split of the data set into the estimates and validation datasets, the same data must be used for both procedures (Davison and Hincley, 1997). This implies the use of Jack Knife method in this present research. When applying this method the fitted model shows some bias due to a small number of trees on the data with large dimension.

CONCLUSIONS

This study aim, at developing a system of equations to predict tree biomass for the maritime pine species in Portugal, reveals the following:

1. There is a significant increase in the predictive ability of the stem wood and needles models that include tree height as a predictor in addition to diameter at breast height
2. The use of crown length instead of height in the models for the crown components does not lead to a relevant increase in the model predictive ability
3. There is a clear effect of the stand age in the models for the stem components leading to an increase in the model predictive ability.

The proposed models took into account not only the performance of each allometric model but also the requirement that models application depends only on readily available data in current forest inventories. The final models obtained can be used for consistently estimate total aboveground tree biomass and biomass by tree component across regional boundaries, for the maritime pine species in Portugal. Consequently, this will be a useful tool for monitoring changes in carbon stocks in maritime pine even or uneven-aged stands.

ACKNOWLEDGEMENTS

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III. MODELLING BIOMASS EXPANSION FACTORS FOR THE MOST IMPORTANT FOREST TREE SPECIES IN PORTUGAL

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Abstract

The Portuguese National Inventory Report on Greenhouse Gases 1990-2004 (NIR) has been based on a set of biomass expansion factors (BEF) that were estimated on the basis of published National Forest Inventory (NFI) data. Since then, several studies have been carried out in order to develop allometric equations for the most important forest tree species in the country. Current allometric equations were used for each species in this study, in order to estimate stand volume and stand biomass for a large set of plots representing different regions, sites and stages of stand development. Biomass expansion factors were computed for each plot, and afterwards its dependence on site and stand variables were studied. The results of this study support a critical analysis of the biomass expansion factors that had been used previously to estimate carbon stocks in the Portuguese NIR. Models to predict BEF as a function of stand variables were developed for each one of the species, and the regarding biomass estimates validated with data from the 2005-2006 National Forest Inventory.

Keywords: biomass expansion factor, allometric equations, carbon stocks

INTRODUCTION

Forest management and growth of new plantations are recognized as one possible tool countries may adopt in the framework of the Kyoto Protocol, to reduce greenhouse gases (Lindner and Karjalainen, 2007). Thus, the need in achieving accurate and precise measurements of the carbon sequestered in forests and to standardize the definitions and methods used in national forest inventories concerning CO_2 sink is gaining relevance (Brown, 2002; Löwe et al., 2000). Previously mentioned authors describe several studies throughout Europe, focused on the improvement of methods for volume conversion into biomass. Carbon sequestration evaluation is based on estimates of forest biomass. Direct estimates are obviously very expensive, as they imply destructive sampling of trees. Therefore, this leads to the use of other methods for quantifying aboveground biomass (de Wit et al. 2006). Two methods are usually applied for biomass estimates, biomass expansion factors (BEF) and tree allometric equations. The second method can provide stand biomass estimates, with an accuracy similar to the one obtained with traditional volume equations, which are usually considered appropriate for most practical applications. In order to obtain stand biomass the stand volume is simply multiply by the constant BEF value. The BEF can be applied to readily processed data which, in some cases, is an advantage to the use of tree allometric equations. The use of BEF is also highly needed for biomass and carbon stock estimates in growth and yield models without a biomass module, which happens in most cases for traditional empirical models. The Portuguese National Inventory Report (NIR) on Greenhouse Gases for the period 1990-2006 (Ferreira et al., 2008, table III-1) has been based on a set of constant BEF values estimated on the basis of published NFI data (Pereira et al., 2002). Several authors (e.g. Schroeder et al., 1997; Lehtonen et al., 2004; Soares and Tomé, 2004) found that the BEF are not constant but else depends on stand variables, namely on the stage of stand development. In the last few years in Portugal, several studies have focused on the development of allometric equations for the most important forest species in the country, mainly: maritime pine (*Pinus pinaster*) (Pascoa et al., 2004, Lopes, 2005), eucalyptus (*Eucalyptus globulus)* (António et al., 2007), cork oak (*Quercus suber)* (Tomé et al., 2007b), holm oak (*Quercus ilex)* (Paulo et al., 2003), pyrenean oak (*Quercus pyrenaica)* (Carvalho, 2003) and umbrella pine (*Pinus pinea*) (Correia et al., 2008b), sweet chestnut (*Castanea sativa)* (Patrício, 2004; Patrício et al., 2005). The first four species correspond to 84% of the Portuguese forest area and the last two species are becoming increasingly important due to the rise in its new plantations (Tomé et al., 2007a). This study considers five of these species where data from permanent plots are available for model development: maritime pine, eucalyptus, cork oak, umbrella pine and chestnut. The main goal is to analyze the accuracy of the constant BEF used in the Portuguese NIR, using them and the tree allometric equations to estimate stand biomass for a large set of field plots representing different regions, sites and stages of stand development. The second goal is to analyze possible relationships between the BEF and stand variables, and to develop models in order to make predictions of BEF that can be later used to obtain better biomass estimates than the previously obtained estimates with constant BEF value.

Table III-1 Biomass expansion factors used in the Portuguese NIR (Ferreira et al., 2008)

Species	Stem volume conversion factor into	
	Aboveground biomass	Total biomass
Pinus pinaster	0.78	1.03
Eucalyptus globulus	0.70	0.87
Quercus suber	0.57	0.82
Pinus pinea	0.84	1.11
Castanea sativa	0.56	0.80
Other *Quercus* sp.	0.57	0.82

METHODS

Data

Data for this study came from several sources. Two data sets were used for each one of the five species, one for the analysis of the stand variables that influence the value BEF and subsequent fit of models for prediction of BEF (fitting data set) and another for validation purposes (validation data set). The fitting data set consists of data from permanent plots and trials. All the validation data sets came from the 2005-2006 Portuguese National Forest Inventory (NFI). In the Portuguese National Forest Inventory all the trees inside a circular plot (area between 500 and 2000 m^2 depending on the species) with a diameter at breast height larger than 7.5 cm (5 cm for eucalyptus) are measured. However measurements on permanent plots and trials include all the trees inside the plots. The predictive models for BEF were based on data from the permanent plots considering two approaches, one with all the trees inside the plot and the other considering the diameter threshold of the NFI. As the objective for using the BEF is to estimate stand biomass from stand volume estimated in forest inventories, NFI data were used to study the impact of these two approaches.

Biomass expansion factors were computed, considering stand total aboveground biomass and stand volume, whose definition depended on the species:

Pines, eucalyptus and chestnut

$$BEF\ (Mg\ m^{-3}) = \frac{Wa}{V}$$

$$BEFdt\ (Mg\ m^{-3}) = \frac{Wadt}{Vdt}$$

Cork oak

$$BEF_{di}(Mg\ m^{-3}) = \frac{Wa}{V_{di}}$$

$$BEFdt_{di}(Mg\ m^{-3}) = \frac{Wadt}{Vdt_{di}}$$

where *Wa* is stand aboveground biomass, *V* is total stand volume and V_{di} is stand volume to a top diameter of 7.5 cm. Volume for the cork oak species (V_{di}) includes stem volume and volume from the main branches to a top diameter of 7.5 cm. Biomass expansion factors were also computed considering the NFI threshold (BEF*dt*), excluding trees above a diameter of 7.5 cm (5 cm for eucalyptus), where the prefix *dt* indicates the diameter threshold considered.The same methodology was used for all the species.

Several stand variables were computed for each one of the plots: stand density (N), dominant height (hdom), site index (S), age (t), quadratic mean diameter (dg) and basal area (G); as well as stand volume and stand biomass as defined above. Stand biomass and total volume were obtained as the sum of tree biomass and tree volume estimated with allometric equations applied by species (table III-2). The IPCC default value for the carbon fraction of dry matter (default =0.5) was used to obtain the carbon stock by simply multiply it by the stand biomass (Ferreira et al, 2008).

Table III-2 References for the allometric equations applied to estimate volume and biomass for each tree species

Species	Volume equations	Biomass equations
Pinus pinaster Aiton	Falcão, 1994	Table II-5
Eucalyptus globulus	Tomé et al., 2007d	António et al., 2007
Quercus suber L.	Tomé et al., 2007b	Tomé et al., 2007b
Pinus pinea L.	Tomé et al., 2007b	Correia et al., 2008b
Castanea sativa Miller	Patrício, 2004	Patrício, 2004

For the cork oak, crown cover was also computed as this is an important variable in this species management. Note that for the cork oak, stand variables were computed under cork, due to the fact that cork is periodically extracted. Tables III-3 and III-4 characterize the fitting and validation data sets.

Table III-3 Characterization of the fitting data sets.

Species		N (ha)	dg (cm)	hd (m)	G (m^2ha^{-1})	V (m^3ha^{-1})	V_{di} (m^3ha^{-1})
Pinus pinaster	min	200	2.5	2.8	0.6	1	
(176 plots)	mean	1365	13.8	11.4	22	134.2	
(758 remeasurements)	max	5000	31.3	28.3	60.8	511.6	
Eucalyptus globulus	min	450	2.6	4.32	0.6	1.3	
(177 plots)	mean	1429	12.9	19.5	18.1	166.8	
(1687 remeasurements)	max	4922	26.8	36.8	64.5	866.5	
Quercus suber	min	20	4.2		0.2		1.1
(405 plots)	mean	197	26.6		6.2		40.4
(585 remeasurements)	max	1928	72.9		23.1		154.2
Pinus pinea	min	20	9.3	3.8	0.3	0.9	
(130 plots)	mean	166	35.9	11.3	9.4	50.5	
(no remeasurements)	max	1138	74.7	19.6	25.8	175.1	
Castanea sativa	min	79	3.1	3.2	0.8	1.1	
(68 plots)	mean	724	26.5	18.3	26.7	252.1	
(no remeasurements)	max	2133	51.8	29.9	87.9	850.5	

Table III-4 Characterization of the validation data sets.

Species		N (ha)	dg (cm)	hd (m)	G (m^2ha^{-1})	V (m^3ha^{-1})	V_{di} (m^3ha^{-1})
Pinus pinaster (1280 plots)	min	5	7.5	4.4	0.04	0.20	
	mean	449	21.3	13.9	14.57	115.07	
	max	3658	65.3	36.5	80.25	928.28	
Eucalyptus globulus (978 plots)	min	20	5.3	4.7	0.04	0.22	
	mean	745	12.7	15.9	8.81	71.73	
	max	3619	67.4	38.2	70.07	1314.87	
Quercus suber (1136 plots)	min	5	4.9	2.9	0.01		0.09
	mean	70	33.2	8.9	5.34		34.99
	max	615	105.9	17.7	43.58		293.11
Pinus pinea (180 plots)	min	5	7.6	2.0	0.09	0.19	
	mean	114	32.9	9.6	6.99	35.69	
	max	819	80.5	26.8	48.30	228.81	
Castanea sativa (30 plots)	min	20	8.7	4.5	0.12	0.37	
	mean	225	23.5	10.1	7.64	46.67	
	max	739	129.1	40.0	31.90	439.57	

Relationship between BEF and stand variables

Plots of BEF over each one of the stand variables were first examined in order to detect any possible tendencies and to test the hypothesis that the BEF used in the Portuguese NIR give adequate biomass predictions (or not). The analysis of these plots allowed the selection of the variables to be used as predictors in the models for BEF prediction as well as the shape of the relationships.

Developing models to predict BEF as a function of stand variables

Taking into account the graphical relationships between BEF and the stand variables shown, several functions that adapt to the shape of the relationships were tested and the rectangular hyperbole was found to be the function with a superior performance for most of the relationships:

$$\mathrm{BEF} = \frac{X}{\alpha + \beta \ X}$$

where α and β are parameters to be estimated and X is a stand variable.

In order to select the best predictor this function was fitted for each species considering each one of the stand variables as regressor. In most cases the relationship initially follows a rectangular hyperbole function that tends to linear after a certain point. Thus, a segmented model joining a rectangular hyperbole to a linear function was used. The models were fitted using non-linear regression analysis techniques with the procedure PROC NLIN of the SAS software (SAS Institute Inc, 2004). Regression assumptions – normality and homocedasticity of the errors – were tested through QQ-plots and plots of studendized residuals over predicted values. Non-normality of the errors was overcome by using iteratively reweighted least squares regression with the Huber function to reduce the influence of data points containing large errors on fit (Myers, 1990).

Weighted regression was used to correct heterocedasticity, and weights were found with the methodology used by Parresol (1999). Model fitting was assess by model efficiency, computed as

$$Ef = 1 - \frac{\sum_{i=1}^{n}\left(y_i - \hat{y}_i\right)^2}{\sum_{i=1}^{n}\left(y_i - \bar{y}\right)^2},$$

where, n is the number of observations in the fitting data set, y_i is the observed value and $\hat{y}_i$ is the predicted value for observation i and $\bar{y}$ is the mean of the observed values.

Validation of the present BEF and of the proposed models

Validation was based on the prediction residuals (rp = observed – predicted) computed with the validation data sets. The more precise biomass estimates were given by the individual tree allometric biomass equations application. The variables under study were the aboveground stand biomass computed with and without the NFI diameter threshold (*dt*). Several statistics were computed with the prediction residuals:

1. Model bias evaluated with the mean of the prediction residuals (Mres).
2. Model precision evaluated with the mean of the absolute values of the prediction residuals (Mares) and with the 5th (P5) and 95th (P95) percentiles of the prediction residuals.
3. Model efficiency, computed as above.

Bias in national carbon stock estimates when using the constant BEF

Using data from the 2005-2006 Portuguese National Forest Inventory total carbon stock was estimated for each one of the five species (pure and mixed stands) using the following methodologies:

1. Individual tree allometric equations (assumed as the best estimate)
2. Aboveground constant BEF from table III-1
3. The proposed models to predict BEF

The results were compared in order to assess if the proposed methodology represents a real improvement in relation to the presently used BEF methodology.

Note that the models to predict BEF were developed for pure stands, but the validation data sets included also mixed-stands. The goal was to analyze if the proposed models could be used in this situation.

RESULTS

Analysis of the relationship between BEF and the stand variables

Figures from III-1 to III-5 present the plots of BEF values over several stand variables. The constant BEF used in the Portuguese NIR presented in table III-1 is also plotted for easy visual inspection. The figures show there is a large variation in the BEF values, fact that does not support the use of a constant BEF. For each species there is a clear pattern between the BEF relationship with at least one stand variable indicating a good opportunity for modelling. The relationships between BEF and stand variables show different patterns for the wood production species with clear apical dominance – maritime pine (figure III-1), eucalyptus(figure III-2) and chestnut (figure III-5), and for the species without apical dominance - cork oak and umbrella pine (figure III-3 and III-4). BEF values for the first group of species, with exception of stand density, show a decreasing pattern, close to a rectangular hyperbole with all the stand variables, presenting an initial decreasing tendency which almost vanishes after a certain point. The decreasing phase of the curve is different from variable to variable. Regarding the cork oak and umbrella pine (figure III-3 and III-4) there is a clear tendency of BEF values with stand density and quadratic mean diameter although the patterns for the two species are different. Relationships between BEF and stand variables are not as clear as in the wood production species. Figures III-1 and III-2 show that the constant BEF used in Portuguese NIR for maritime pine and eucalyptus overestimates stand biomass with less bias in young stands than in older stands. The constant BEF used for the cork oak and umbrella pine (figure III-3 and III-4) clearly underestimate biomass for all types of stands. In chestnut (figure III-5) the stand biomass is overestimated in young stands however in the older chestnut stands bias is not important.

Modelling BEF as a function of stand variables

Table III-5 shows the models that were selected for each one of the species as well as the parameter estimates and modelling efficiency, for the two sets of data with and without considering the diameter threshold from the NFI. The best fitting for the species with apical dominance (maritime pine, eucalyptus and chestnut) was obtained with the stand variable dominant height. For the umbrella pine and cork oak the quadratic mean diameter was the variable that better expressed the BEF evolution. Stand density was also important to predict BEF in the umbrella pine species. Most of the models fitted quite well, with modelling efficiencies around 0.9, except for the cork oak and umbrella pine. The variables selected as predictors, dominant height and quadratic mean diameter, are easily available on forest inventories which guarantees the operationally of the models.

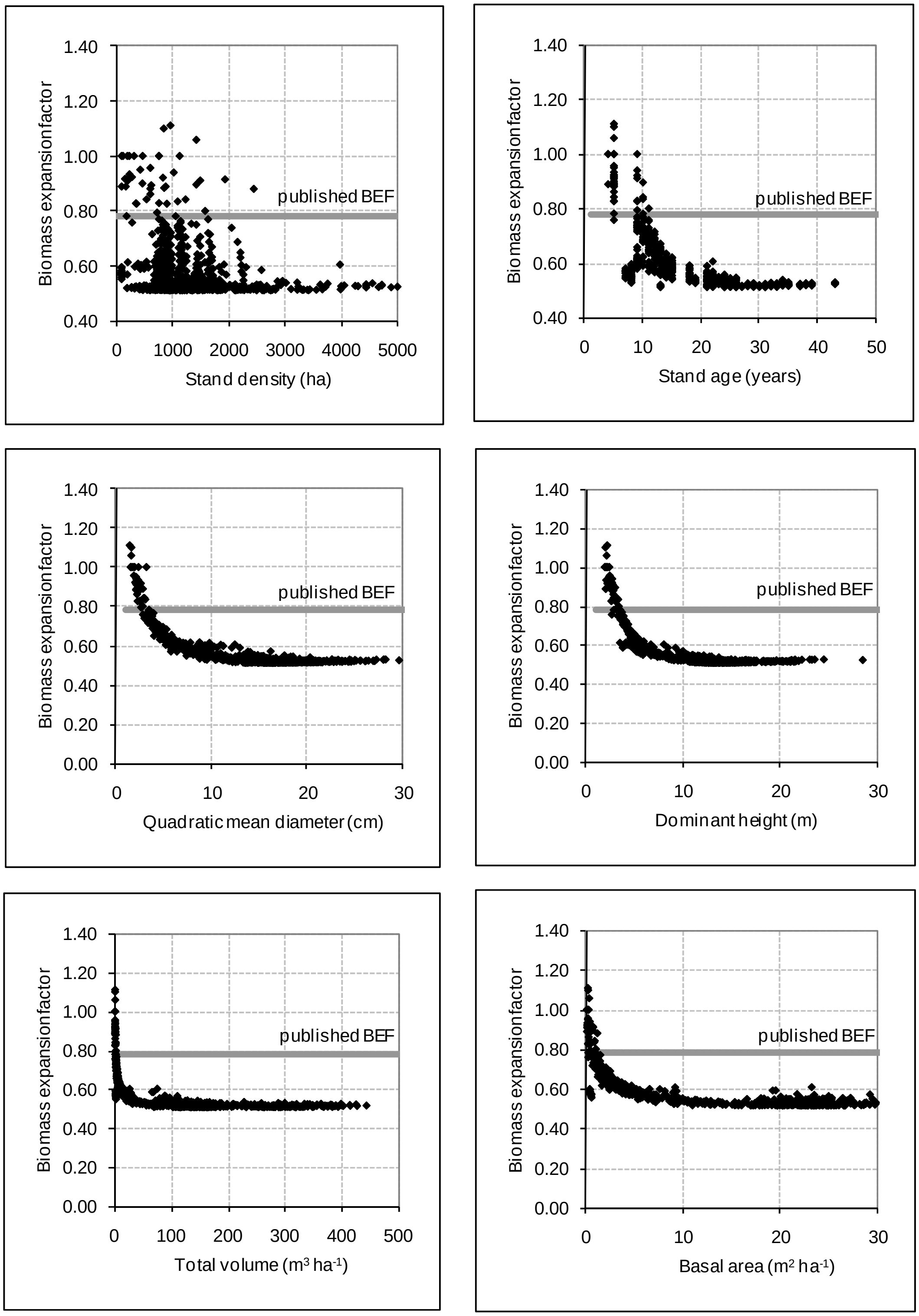

Figure III-1 Evolution of BEF values with stand density, stand age, dominant height, site index, quadratic mean diameter and stand volume for *Pinus pinaster*

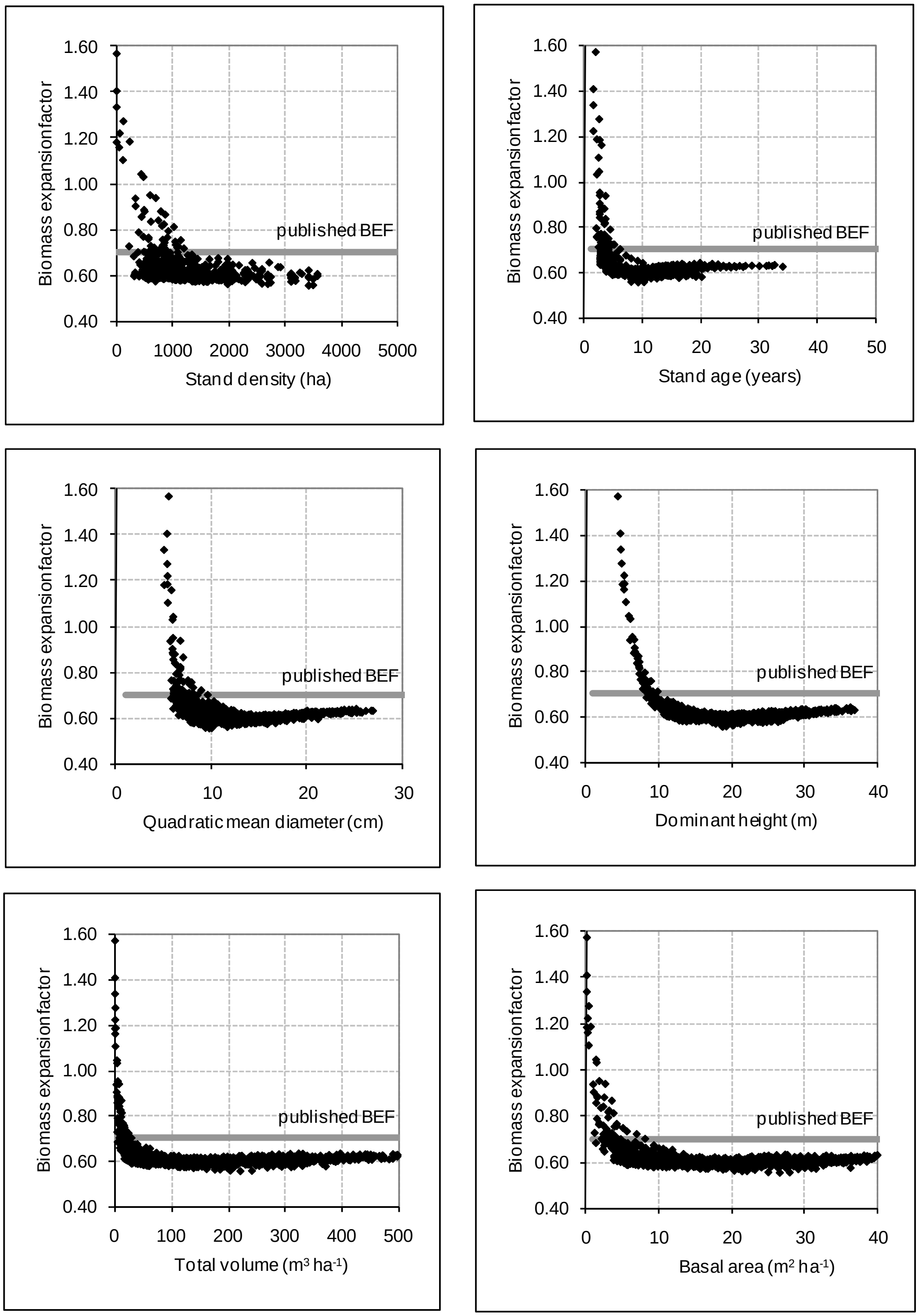

Figure III-2 Evolution of BEF values with stand density, quadratic mean diameter, stand age, basal area, stand volume and dominant height for *Eucalyptus globulus*

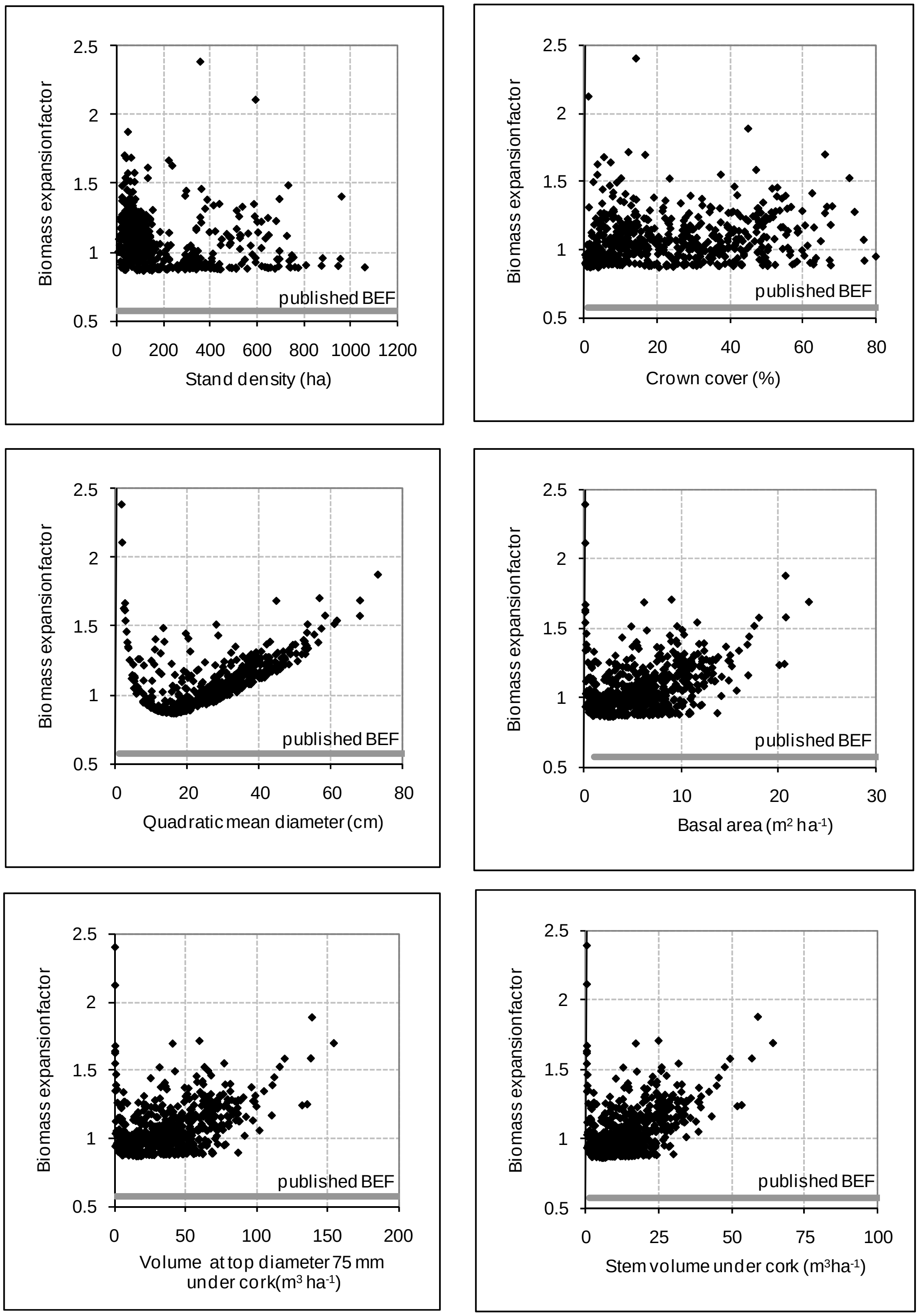

Figure III-3 Evolution of BEF values with stand density, crown cover, quadratic mean diameter under cork , basal area under cork and stand volume under cork for *Quercus suber*

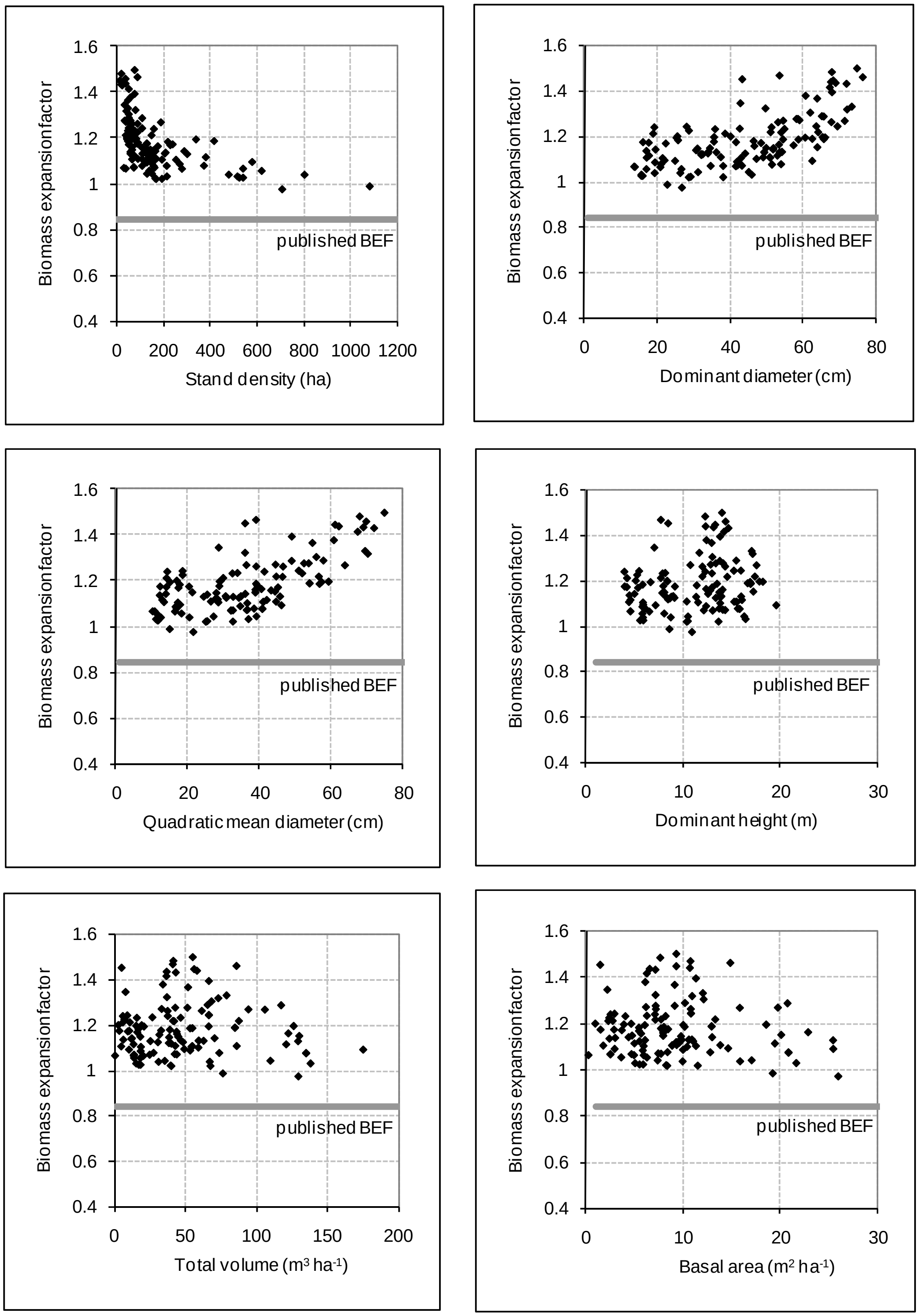

Figure III-4 Evolution of BEF values with stand density, quadratic mean diameter, dominant diameter, basal area, stand volume and dominant height for *Pinus pinea*

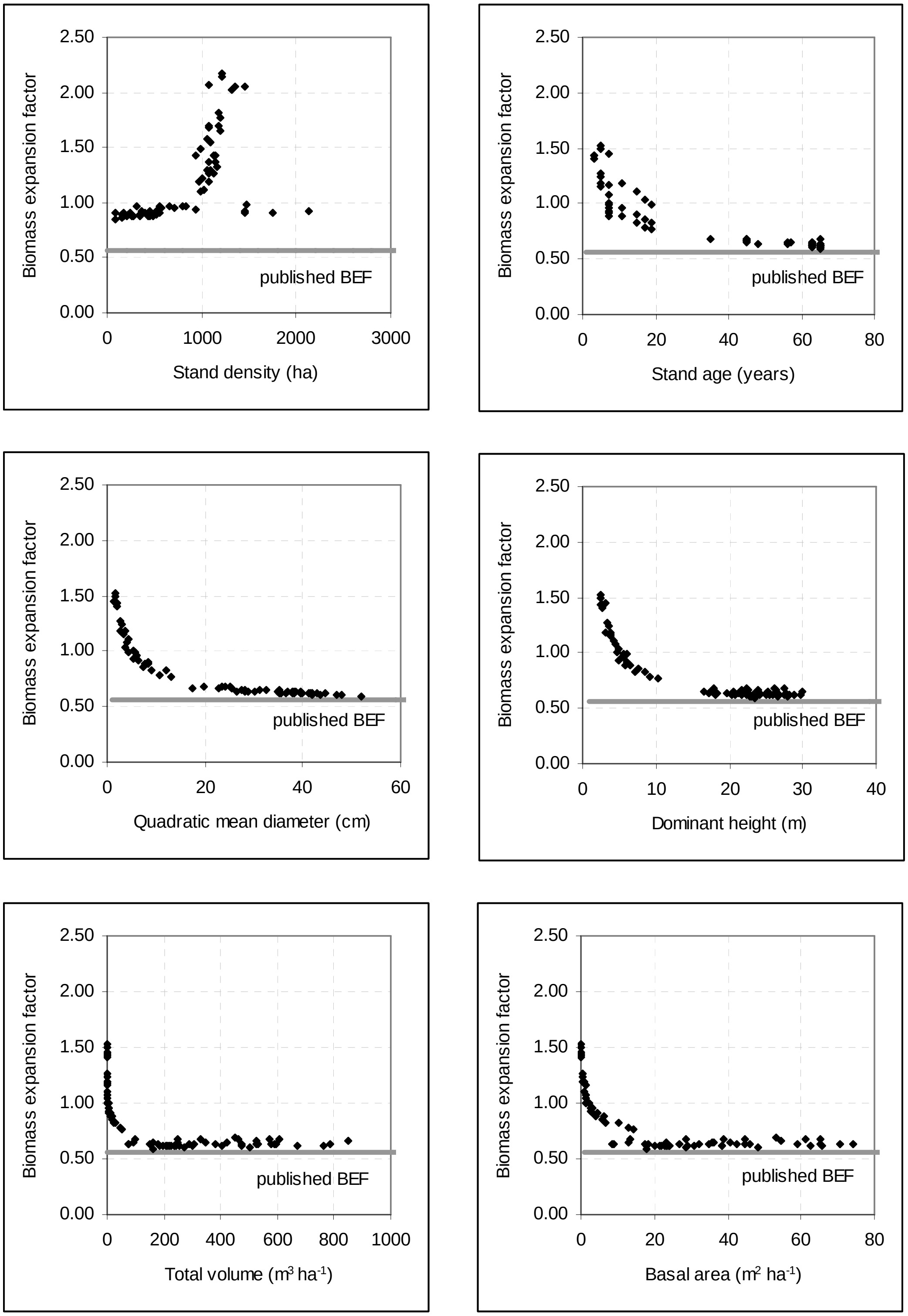

Figure III-5 Evolution of BEF values with stand density, quadratic mean diameter, stand age, basal area, stand volume and dominant height for *Castanea sativa*

Table III-5 BEF models and their parameter estimates

$$[1]\ BEF = \frac{hdom}{\alpha + \beta\ hdom} \qquad [4]\ BEF = \frac{N}{\alpha + \beta\ N + \lambda\ N\ dg}$$

$$[2]\ BEF = \frac{\varepsilon}{\alpha + \beta\ \varepsilon} + \lambda * (hdom - \varepsilon) \qquad [5]\ BEF = \frac{hdom}{\alpha + \beta\ hdom} + \lambda * hdom$$

$$[3]\ BEF = \frac{dug}{\alpha + \beta\ dug} + \lambda * dug$$

Species	Variable	Model		α	β	λ	ε	Ef
Pinus pinaster	BEF	1	*hdom* ≤ ε	-3.1233	2.1968		11.7360	0.937
	BEF	2	*hdom* > ε	-3.1233	2.1968	0.00021		
	BEF*dt*	5		-2.1205	2.1262	0.00100		0.853
Eucalyptus globulus	BEF	1	*hdom* ≤ ε	-6.3005	2.1270		14.9095	0.938
	BEF	2	*hdom* > ε	-6.3005	2.1270	0.00141		
	BEF*dt*	1	*hdom* ≤ ε	-6.1329	2.1051		15.0634	0.883
	BEF*dt*	2	*hdom* > ε	-6.1329	2.1051	0.00110		
Quercus suber	BEF	3		-3.3176	1.6340	0.01380		0.617
	BEF*dt*	3		-5.8441	1.9271	0.01600		0.747
Pinus pinea	BEF	4		-3.6912	0.9689	0.00191		0.539
	BEF*dt*	4		-3.2351	0.9751	0.00216		0.561
Castanea sativa	BEF	5		-2.6140	1.5205	-0.00300		0.932
	BEF*dt*	5		-3.4151	1.7256			0.906

Validation of present BEF and of the proposed models

Table III-6 shows the validation statistics for the biomass estimates based on the Portuguese NIR's constant BEF and with each of the proposed models. As can be seen the use of a constant BEF provides largely biased estimates when compared with the biomass estimated with tree allometric equations. The two models, either using BEF or BEF*dt* as dependent variable, originate unbiased and precise estimates for pure and mixed stands. Note that when using BEF*dt* the volume is also estimated with the same threshold.

Estimates of bias in national carbon stock estimates when using the constant BEF

Table III-7 and III-8 show the national carbon stock estimates obtained with the three methodologies against estimates based on tree allometric equations. Table III-7 presents results for each species by stand type and table III-8 shows it by NUT II region. There is no clear tendency either by stand type or by region. The proposed models provide reasonable estimates across stand types and NUT II regions. Figure III-6 compares the biomass estimate for each field plot by plotting them against stand volume. As can be seen, when applying a constant BEF for the species umbrella pine and cork oak the carbon stock is clear underestimated, while for the maritime pine the carbon stock is overestimated. For the two other species (eucalyptus and chestnut) this difference is not so significant. The carbon stock estimates are similar when applying the two predictive BEF models with and without the diameter threshold from NFI and those results are close to the results obtained with the biomass equations method.

Table III-6 Validation statistics for the biomass estimates with the methodologies tested under this study

Species	Method	nd	Mres	Mares	P5	P95	Ef
Pinus pinaster	NIR	1280	-28.9904	28.9904	-85.9041	-1.0514	0.567
	BEF	1280	0.7926	1.0677	-0.6714	4.0335	0.998
	BEF*dt*	1280	1.0020	1.2808	-0.7681	5.3932	0.998
Eucalyptus globulus	NIR	978	-4.9347	5.4798	-18.9852	1.2502	0.975
	BEF	978	2.0225	2.0954	-0.1521	6.7561	0.985
	BEF*dt*	978	2.0137	2.0800	-0.1042	7.3415	0.984
Quercus suber	NIR	1136	22.0998	22.0998	1.4738	62.5853	0.306
	BEF	1136	1.0421	2.1182	-2.5841	7.0334	0.986
	BEF*dt*	1136	0.9555	2.3009	-3.5080	6.4882	0.986
Pinus pinea	NIR	180	11.8085	11.8085	0.5643	36.4258	0.830
	BEF	180	-2.3365	4.0253	-10.3743	4.9046	0.946
	BEF*dt*	180	-1.6939	3.4210	-9.8512	5.1542	0.978
Castanea sativa	NIR	30	2.5374	3.7019	0.1058	8.5270	0.984
	BEF	30	-3.5907	3.5908	-17.8465	-0.0060	0.980
	BEF*dt*	30	-3.0477	3.2891	-13.6432	1.0714	0.967

Table III-7 National carbon stocks estimated using tree allometric equations and the three methodologies tested under this study by stand type

Species	Stand Type	Number of plots	Area(ha)	Stand Volume (1000m^3)	Carbon Stock (1000 Mg)			
					Biomass equations	Constant BEF	Model BEF	Model BEFdt
Pinus pinaster	Pure	1514	680080	59882	15781	23354	15694	15641
	Dominant	279	143860	12579	3343	4906	3353	3336
	Dominated	202	123120	5055	1343	1971	1187	1184
	Total	**1995**	**947060**	**77516**	**20467**	**30231**	**20233**	**20161**
Eucalyptus globulus	Pure	1118	566132	28115	8848	9840	8660	8665
	Dominant	166	92207	5785	1836	2025	1775	1773
	Dominated	127	101212	5019	1641	1757	1527	1526
	Total	**1411**	**759551**	**38919**	**12325**	**13622**	**11962**	**11964**
Quercus suber	Pure	967	542492	18818	11241	5363	10269	10975
	Dominant	182	119446	2693	1633	767	1492	1598
	Dominated	220	103113	1698	1077	484	1007	1084
	Total	**1369**	**765050**	**23208**	**13952**	**6614**	**12768**	**13658**
Pinus pinea	Pure	102	53544	1723	989	724	1006	1003
	Dominant	62	30386	868	528	365	559	556
	Dominated	64	44916	630	378	265	468	435
	Total	**228**	**128847**	**3221**	**1895**	**1353**	**2033**	**1994**
Castanea sativa	Pure	36	24134	1021	323	286	287	275
	Dominant	7	4076	68	22	19	25	24
	Dominated	12	4852	23	7	6	5	4
	Total	**55**	**33062**	**1112**	**352**	**311**	**316**	**303**

Table III-8 National carbon stocks estimated using tree allometric equations and the three methodologies tested under this study by NUT II region

Species	NUT II Region	Plots number	Area(ha)	Stand Volume (1000m3)	Carbon Stock (1000 Mg)			
					Biomass equations	Constant BEF	Model BEF	Model BEFdt
Pinus pinaster	Norte	414	264376	20373	5392	7945	5383	5367
	Lisboa	33	20361	1689	445	659	453	451
	Centro	1305	592054	52432	13832	20449	13595	13539
	Alentejo	229	65454	2890	763	1127	768	769
	Algarve	14	4815	131	35	51	34	35
	Total	**1995**	**947060**	**77516**	**20467**	**30231**	**20233**	**20161**
Eucalyptus globulus	Norte	236	155077	10761	3505	3766	3278	3276
	Lisboa	31	15558	959	301	336	284	284
	Centro	823	404537	22227	6928	7779	6860	6859
	Alentejo	32	14212	196	63	69	62	62
	Algarve	289	170166	4777	1528	1672	1478	1482
	Total	**1411**	**759551**	**38919**	**12325**	**13622**	**11962**	**11964**
Quercus suber	Norte	47	11414	130	78	37	63	70
	Lisboa	48	27927	898	534	256	476	511
	Centro	120	40809	666	389	190	336	367
	Alentejo	1081	655348	21207	12789	6044	11759	12561
	Algarve	73	29551	307	162	87	134	149
	Total	**1369**	**765050**	**23208**	**13952**	**6614**	**12768**	**13658**
Pinus pinea	Norte	1	800	0	0	0	0	0
	Lisboa	18	13680	362	221	152	231	227
	Centro	22	3926	209	119	88	124	124
	Alentejo	13	6002	76	43	32	42	42
	Algarve	174	104438	2574	1512	1081	1636	1601
	Total	**228**	**128847**	**3221**	**1895**	**1353**	**2033**	**1994**
Castanea sativa	Norte	31	27985	962	309	269	270	257
	Lisboa	1	150	0	0	0	0	0
	Centro	19	4402	51	17	14	16	16
	Alentejo	4	525	99	27	28	30	31
	Algarve	0	0	0	0	0	0	0
	Total	**55**	**33062**	**1112**	**352**	**311**	**316**	**303**

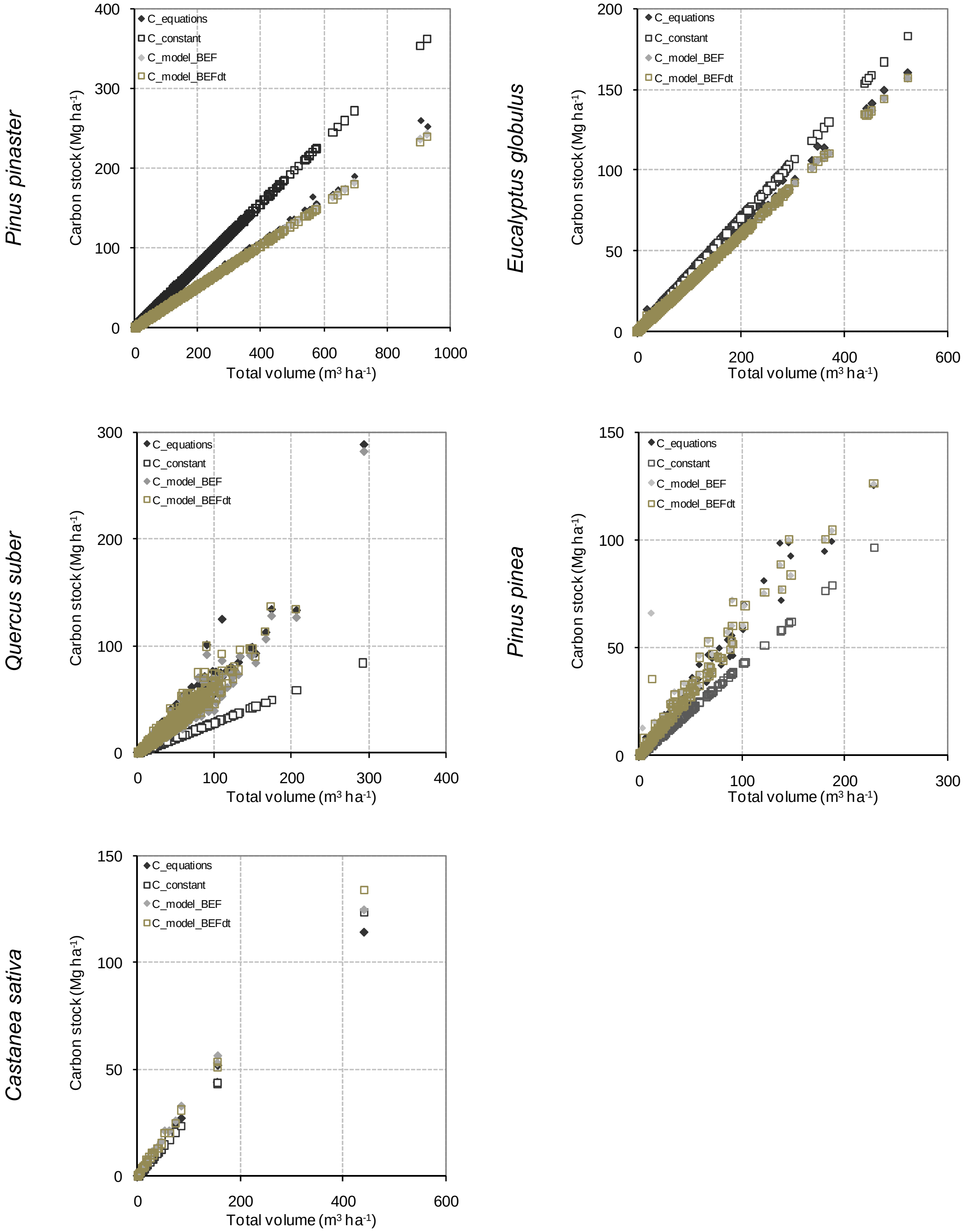

Figure III-6 National carbon stock comparison between the three methodologies tested and the estimating based on tree allometric equations

DISCUSSION

The objective of this research was to analyze the accuracy of the methodology presently used for biomass estimates in the Portuguese National Inventory Report on Greenhouse Gases submitted under the United Nations Framework Convention on Climate Change and the Kyoto protocol. According to the used methodology carbon stocks are estimated on the basis of a constant BEF for each species. As shown in other studies (Schroeder et al., 1997; Lehtonen et al., 2004; Soares and Tomé, 2004) the research presented here does not support the use of a constant BEF.

In the wood production species characterize by apical dominance (maritime pine, eucalyptus and chestnut), there is a clear relationship between the BEF and the considered stand variables, with exception for the stand density. For those species the dominant height was selected because it is a common variable to express the stand stage of development and also because it showed the best fitting comparing with other stand variables. In the cork oak and umbrella pine the variable that expressed a better pattern with the stand stage of development was the quadratic mean diameter, although for the second species the stand density also revealed a decreasing tendency. For the wood production species the BEF decreases as the stands develops, tending to a constant value as the stands get older, while for the cork oak and umbrella pine the BEF increases with the quadratic mean diameter. The different pattern probably can be explained for the apical dominance absence in the cork oak and umbrella pine.

The results for the wood production species are in agreement with the findings of António et al. (2007) and Porté et al. (2002) when developing individual tree allometric equations. The first author found that expressing at least one of the parameters of the equations as a function of dominant height increased the precision of estimates and the second one found a similar result with the stand age. The results of the two studies showed, as presented here, that biomass estimates are dependent on the stage of tree/stand development.

Schroeder et al. (1997) discuss the fact that smaller trees are generally a larger component of aboveground biomass in low biomass stands. Two models for BEF prediction were developed for each species, one using the BEF computed with all the trees in the stand (BEF) and another excluding trees with a diameter smaller than the NFI threshold (BEF*dt*). When validated with data from the 2005-2006 Portuguese NFI, the two models performance was similar, indicating that it is possible to use the same model for estimates of total stand biomass and estimates of biomass above a diameter threshold, provided that the BEF are multiplied by the given volume estimates. This result is important because implies that the model fitted when all trees are considered is flexible enough to allow estimation of biomass when a diameter threshold is considered. Thus, the same model can be used even if there will be changes in the diameter threshold.

Another interesting result is the good performance achieved by the models for BEF prediction when applied to mixed stands or for different regions.

CONCLUSIONS

Some important conclusions could be drawn from the research presented in this paper:

- There is a large variability in the BEF values for the same species, fact that does not support the estimates of stand biomass with a constant BEF.
- There is a clear pattern for the relationship between BEF and several stand variables that are related to the stage of stand development and this relationship is clearer in wood production species.
- It is possible to model BEF as a function of some stand variable – dominant height (hdom) and quadratic mean diameter (dg) – and the estimates provided by these models are similar to the ones obtained with individual tree allometric equations.
- A model that predicts a BEF based on total aboveground stand biomass can be used to predict stand aboveground biomass above a diameter threshold, provided that it is multiplied by their volume.
- A model developed for the whole country performs reasonably well when applied t different regions.
- A model that predicts BEF for pure stands perform reasonably well when applied to mixed stands.

ACKNOWLEDGEMENTS

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IV. CONCLUSÃO

Este trabalho foi composto por dois estudos apresentados em capítulos distintos sob formato de artigo. Os dois estudos encontram-se ligados pela espécie pinheiro bravo e têm como contributo fornecer instrumentos para a quantificação de biomassa e de carbono na floresta portuguesa.

No primeiro estudo obteve-se dois sistemas de equações de biomassa, que permitem estimar a biomassa total aérea e as suas componentes ao nível da árvore para a espécie pinheiro bravo (*Pinus pinaster*) em Portugal. Em ambos os sistemas foi tido em conta não só a melhor performance dos modelos seleccionados como a integração de variáveis facilmente disponíveis ao nível dos dados de inventário florestal. A selecção de um dos sistemas será feita de acordo com a necessidade de estimar a biomassa aérea da árvore em povoamentos irregulares ou povoamentos regulares de idade desconhecida ou em povoamentos regulares de idade conhecida. A possibilidade de estimar a biomassa da árvore nas suas diversas componentes permite avaliar o impacto de operações florestais, nomeadamente o impacto de diferentes intensidades de exploração no ciclo de nutrientes.

O objectivo principal deste trabalho reproduz-se no segundo estudo, através de uma análise crítica na aplicação de diferentes métodos para a estimação da biomassa do povoamento para algumas das principais espécies florestais portuguesas. Neste estudo, foram analisados graficamente os valores de BEF, obtidos pela razão entre a biomassa total acima do solo e o volume total do povoamento, em função de diferentes variáveis do povoamento, para as seguintes espécies florestais: pinheiro bravo, eucalipto, sobreiro, pinheiro manso e castanheiro. Para cada espécie foram aplicadas as actuais equações de biomassa ao nível da árvore, cujo somatório resulta na biomassa do povoamento. Como método alternativo, foram aplicados os factores de expansão de biomassa (BEF), publicados por espécie, no relatório do Inventário Nacional de Emissões por Fontes e Remoções por Sumidouros de Poluentes Atmosféricos, os quais permitem estimar a biomassa, pela simples multiplicação destes valores constantes pelo volume do povoamento. Com base na conclusão de diversos estudos de que o factor de expansão de biomassa não é constante ao longo do tempo, foram ajustadas equações para estimar factores de expansão de biomassa em função de variáveis do povoamento facilmente obtidas com os dados de inventário florestal. Os resultados da aplicação destas equações para estimar a biomassa do povoamento, foram comparados com os resultados obtidos com os métodos alternativos.

A utilização de factores de expansão de biomassa, em relação à determinação da biomassa com recurso a equações alométricas da árvore, tem a vantagem de ser aplicável em dados já processados e em modelos de crescimento do povoamento que não incluem o módulo de biomassa. A importância de equações para estimar valores de BEF deve-se ao facto da aplicação de valores de BEF constantes não ser adequada para estimação de biomassa, uma vez que estes valores variam com o estado de desenvolvimento do povoamento.

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