Biomass expansion factors for *Eucalyptus globulus* stands in Portugal

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Abstract

One of several procedures for estimating carbon stocks in forests is the estimation of tree or stand biomass based on forest inventory data. The two approaches normally used to convert field measurements of trees to stand biomass values are allometric biomass equations and biomass expansion factors (BEFs). BEFs are used in published National Forest Inventory results in which biomass is not estimated or as a complement of growth models that do not include biomass predictions. In this paper, the effectiveness of BEFs for estimating total stand biomass in Portuguese *Eucalyptus globulus* plantations was analyzed. Here, BEF is defined as the ratio of total stand biomass (aboveground biomass plus root biomass) to stand volume with bark. To calculate total biomass, an equation was developed to estimate root biomass as a function of aboveground biomass. Changes of BEF with stand variables were analyzed. Strong relationships were observed between BEF and stand age, stand basal area, stand volume and dominant height. Consequently, an equation to predict BEF as a function of stand variables was fitted, and dominant height was selected as the predictor stand variable. Estimates of total stand biomass based on individual tree allometric equations were compared with estimates obtained with a constant BEF (0.77), used in the Portuguese National Inventory Report on Greenhouse Gases, and with estimates obtained using the dominant height-dependent BEF equation developed in this work. The BEF prediction model proposed in this work may be used to improve *E. globulus* Portuguese biomass estimates when tree allometric equations cannot be used.

Key words: root biomass; aboveground biomass; biomass expansion factors; allometric equations.

Resumen

Factores de expansión de la biomasa de rodales de Eucalyptus globulus en Portugal

El objetivo es estimar las reservas de carbono en los bosques mediante la comparación de dos métodos: ecuaciones alométricas de biomasa y los factores de expansión de la biomasa (BEF). Las estimaciones de la biomasa total del rodal, basado en las ecuaciones alométricas de árboles individuales se compararon con las estimaciones obtenidas con unos factores de expansión constante de la biomasa (BEF) de 0.77, utilizados en el Informe del Inventario Nacional de Portugal de gases de efecto invernadero, y con las estimaciones obtenidas utilizando la ecuación de altura dominante de BEF desarrollada en este trabajo. En este trabajo se analizó la eficacia de la BEF para estimar la biomasa total del stand en portugués plantaciones de *Eucalyptus globulus*. Aquí, el BEF se define como el cociente de la biomasa total del stand (biomasa aérea más la biomasa de raíces), situándose el volumen con corteza. Para el cálculo de la biomasa total, se desarrolló una ecuación para estimar la biomasa de raíces en función de la biomasa sobre el suelo. Se analizaron los cambios de BEF con las variables del rodal. Se observó una gran relación entre el BEF y la edad del rodal, el área basal, el volumen y la altura dominante. Por lo tanto, se ajustó una ecuación para predecir el BEF en función de las variables del rodal, seleccionando la altura dominante como la variable independiente predictora. El modelo de predicción de BEF propuesto en este trabajo puede ser utilizado para mejorar las estimaciones de biomasa de *E. globulus* portugueses cuando las ecuaciones alométricas de árboles no se pueden utilizar.

Palabras clave: biomasa de raíz; biomasa aérea; factores de expansión de la biomasa; ecuaciones alométricas.

Introduction

The Good Practice Guidance of Land Use, Land-Use Change and Forestry (GPG-LULUCF) emphasizes the importance of estimating, measuring, monitoring and reporting on carbon stock changes and greenhouse gas emissions from LULUCF activities under Articles 3 (paragraphs 3 and 4), 6 and 12 of the Kyoto Protocol. In general, estimates of carbon stocks and stock changes in temperate and boreal forests are based on forest inventory data (Lehtonen *et al.*, 2004). To estimate carbon stock changes in living biomass, two methods have been suggested (Nabuurs *et al.*, 2003): (a) the default method, which involves subtraction of the biomass carbon loss from the estimated biomass carbon increment for the reporting year, and (b) the stock change method, which involves biomass carbon stock inventories for a given forest area at two time points. In the latter method, biomass change is the difference between biomass at time t2 and t1, divided by the number of years between the inventories.

On the other hand, two methods are normally used to convert field measurements of trees (forest inventory data) to stand biomass values. One is based on biomass expansion factors (BEFs) (Chhabra *et al.*, 2002; Jalkanen *et al.*, 2005; Lehtonen *et al.*, 2004; Levy *et al.*, 2004; Liski *et al.*, 2006; Soares and Tomé, 2004) that convert stand volume to stand biomass. The other method is based on models that reflect the allometric relationship between tree biomass and tree variables. These allometric biomass equations can be functions of diameter at breast height (Brown, 2002; Landsberg and Waring, 1997) or diameter at breast height and total height (António *et al.*, 2007; Bartelink, 1996; Monserud and Marshal, 1999; Reed and Tomé, 1998).

With tree allometric equations, National Forest Inventory (NFI) data can be processed at tree level in order to provide accurate estimates of stand biomass. However, BEFs are still needed (a) in published NFI results in which biomass is not estimated and (b) as a complement of growth models that do not include biomass predictions.

Löwe *et al.* (2000) compared reports for the EU Monitoring Mechanism on Greenhouse Gas Emission and the United Nations Framework Convention on Climate Change of EU15 Member States and identified a lack of transparency, consistency and completeness in Chapter 5, which covers changes in forests and other woody biomass stocks. A key requirement identified by the authors was the need to adopt harmonized approaches and definitions for both land areas and the factors used to expand from stem wood to total biomass (BEF).

BEF can be calculated as the ratio of the biomass to the volume, resulting in a dimensional variable (BEF, Mg m^{-3}), or as the ratio of the biomass to the stem wood biomass (BEF', Mg Mg^{-1}), resulting in a non-dimensional variable:

$$BEF = \frac{W}{V} = \rho \, BEF'$$

where W is the stand biomass (Mg ha^{-1}), ρ is the dry matter basic wood density (Mg m^{-3}) and V is the stand volume (m^{3}ha^{-1}).

Stand biomass can be defined as aboveground stand biomass (Brown, 2002; Levy *et al.*, 2004) or total stand biomass (Soares and Tomé, 2004), and biomass can refer to dry mass (Lehtonen *et al.*, 2004) or to fresh mass (Levy *et al.*, 2004). Stand volume can be defined as merchantable volume (Brown, 2002; Levy *et al.*, 2004) or total volume (Soares and Tomé, 2004) either with or without bark.

BEFs used in the national estimation of C stocks are often based on a few regional studies with limited representation (Joosten *et al.*, 2004). Constant BEFs have been applied (Löwe *et al.*, 2000) despite the fact that BEFs vary depending on growth conditions and the phase of stand development (Lehtonen *et al.*, 2007; Soares and Tomé, 2004; Satoo and Madgwich, 1982 in Lehtonen *et al.*, 2004). To reduce the uncertainty associated with the use of BEFs for biomass estimation, non-constant BEFs have been developed in specific studies to account for variation in the allometry of trees reflecting the stage of stand development. Peichl and Arain (2007) developed age-sensitive equations to predict the BEF for each biomass component. Age-dependent BEFs were also presented by Lehtonen *et al.* (2004), Jalkanen *et al.* (2005) and Tobin and Nieuwenhuis (2007). Brown (2002) describes how changes in BEF vary with the merchantable volume of the stand: high BEFs at low volume, with BEF generally decreasing exponentially to a constant value at high volume. Fang *et al.* (2001) reported BEF as a function of stem volume. Chhabra *et al.* (2002) used BEF as a function of growing stock volume. Stand-level BEFs, which convert stem volume to tree biomass components (foliage, branches, stem wood, bark, stump, coarse

roots, and small roots), were described by Lehtonen *et al.* (2004).

According to the 5th NFI, pure and dominant *Eucalyptus globulus* Labill plantations represent 23.3% of the forest area in Portugal, corresponding to 739,512 ha (AFN, 2010).

E. globulus is the main eucalyptus species cultivated in Portugal and is characterized by high productivity. This fast-growing species is managed according to a relatively simple production system, based on the precocity of fast growth and the sprouting ability after harvest. The majority of the plantations are pure stands with a density of planting between 1,100 and 1,400 trees/ha. Stands are normally exploited in three cutting cycles of 10-12 years each. Stands are managed in a coppice system after the first cutting cycle, and these plantations mainly produce raw material for the pulp industry.

The objectives of this manuscript are to analyze changes in BEF varying with stand characteristics and to analyze the effect of using a constant BEF for estimating total stand biomass in Portuguese *E. globulus* plantations. In this work, BEF is defined as the ratio of the total stand biomass (aboveground biomass plus root biomass) to the stand volume with bark. Several approaches were used to achieve the objectives. First, an equation was developed to estimate stand root biomass. Second, changes in BEF varying with stand variables, including age, density, basal area, dominant height, site index and volume, were analyzed, and an equation was developed to estimate the BEF adjusted to stand characteristics. Finally, estimates of total stand biomass obtained using tree allometric equations were compared with estimates obtained using a constant BEF (0.77), from the Portuguese National Inventory Report (PNIR) on Greenhouse Gases (Pereira *et al.*, 2010), and estimates obtained using the equation proposed for BEF estimation.

Data and methods

In this work, BEF was defined as the ratio of the total stand biomass (aboveground biomass plus root biomass) to the stand volume with bark. Total stand biomass was used to ensure an appropriate comparison with the biomass estimates based on the constant BEF (0.77) used in the PNIR on Greenhouse Gases. To compensate for missing information, it was necessary to develop an equation to predict stand root biomass.

Data

Estimation of stand root biomass

To develop an equation for the estimation of root biomass in Portuguese eucalyptus stands, data was compiled from literature on eucalyptus root biomass obtained by excavation in Portugal. Data were obtained in an experiment with fertilization and irrigation located in the central region of Portugal, 10 km from the Atlantic Ocean, where the climate is Mediterranean with maritime influence (Ribeiro and Lautensach, 1999). This experiment was planted with 3 m × 3 m spacing in March 1986 and consisted of a control and 3 treatments replicated in 2 blocks (Pereira *et al.*, 1989). The treatments were daily irrigation from April to October (I); broadcast application of a pelleted fertilizer twice a year (in March and October) (F); and daily irrigation combined with a simultaneous application of liquid fertilizer once a week during the dry season (FI). One and two years after planting, 24 trees (6 trees per treatment) were selected for root measurements from a group of trees randomly harvested for aboveground biomass measurements (Fabião *et al.*, 1995). Six years after planting, only block 2 was available, and a tree with a diameter near the treatment mean was chosen from each plot, for a total of 4 trees (Fabião *et al.*, 1995). In all cases, root biomass included the tap root and the remaining stump, coarse roots (d ≥ 30 mm), intermediate roots (2 < d < 30 mm) and fine roots (≤ 2 mm).

Stand root biomass was calculated using data from these felled trees. To develop a stand root biomass equation, a total of 12 observations were used (Table 1).

In the fertilization and irrigation trial described above, the root/shoot ratio was highest in C (the control) and lowest in the FI treatment one and two years after planting; 6 years after planting, the highest values were observed in FI and C (Fig. 1). Differences in the root/shoot ratio between the F and I treatments were negligible during the experimental period. The relatively small variation in the root/shoot ratio between different treatments at each age supported the decision to use all published data to fit the stand root biomass equation.

It is important to note that eucalyptus plantations in Portugal are normally exploited in cutting cycles of 10-12 years. The available root data cover only the first half of the rotation length and were obtained from stands regenerated from seedlings. Six years after planting, however, the dimensions of the trees harvested in the irrigated and fertilized plots were similar to those of trees in non-treated stands with an age close to harvest. Ac-
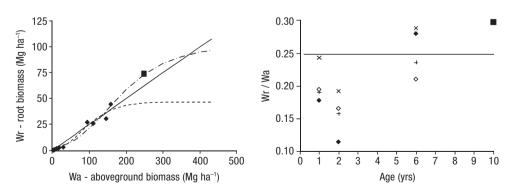
Table 1. Data used to fit an equation for estimating root biomass in Portuguese eucalyptus stands (adapted from Fabião *et al.*, 1995)

Treatment	Age (yrs)	Number of felled trees	Stand root biomass (Mg ha⁻¹)	Stand aboveground biomass (Mg ha⁻¹)
C	1	6	0.48	1.97
	2	6	2.07	10.78
	6	1	27.01	93.66
F	1	6	0.50	2.62
	2	6	2.52	16.07
	6	1	25.86	109.07
I	1	6	0.80	4.12
	2	6	2.83	17.19
	6	1	30.40	144.83
FI	1	6	0.87	4.88
	2	6	3.26	28.61
	6	1	44.16	157.42

(C) control, (F) fertilization, (I) irrigation, and (FI) fertilization plus irrigation.

cording to the 5th NFI, however, 23% of pure and dominant eucalyptus plantations are older than 12 years. In order to complement the information available for large values of stand aboveground biomass, literature describing eucalyptus root biomass in other countries was obtained. Available information for *E. globulus* (Resh *et al.*, 2003) was used to fit the final equation. No information was found for root biomass from coppiced stands.

Changes in BEF with stand characteristics and development of an equation to estimate BEF

Available data from experimental trials and from permanent plots of eucalyptus established in stands managed by the CELBI pulp company were used to analyze changes in BEF varying with stand variables and to develop an equation to estimate BEF. All plots were located in pure even-aged eucalyptus plantations. The size of the plot, the stand age, the dominant height, a sample of total tree heights and the diameter at breast height of all live trees were available from each plot and measurement. From this large database, a subset of information was used to avoid serial correlation. The subset was determined by randomly selecting one measurement from each plot, for a total of 230 observations. Different stages of stand development, site index values, stand ages and stand densities were represented. Table 2 presents the characteristics of the dataset.

Figure 1. Relationship between stand root biomass and stand aboveground biomass and evolution of the ratio Wr/Wa in the experiment located in central Portugal with fertilization and irrigation (data from Fabião *et al.*, 1995). (left) Line: fitted linear equation; dotted line: fitted non-linear equation; sparse dotted line: fitted non-linear equation with inclusion of literature point (Resh *et al.*, 2003). (right) Line: constant value defined by the fitted linear equation; ×: control plots; ◇: irrigation plots; + : fertilization plots; ◆: irrigation and fertilization plots; ■: literature data.

Table 2. Characterization of the stands used to analyze changes in BEF varying with stand characteristics and to develop an equation to estimate BEF (number of observations = 230)

	Age (yrs)	Dominant height (m)	Basal area (m²ha⁻¹)	Stand density (ha⁻¹)	Site index (m)	BEF (Mg m⁻³)
Minimum	0.9	3.4	0.3	481	10.1	0.66
Mean	7.7	17.0	15.0	1,584	21.5	0.80
Maximum	22.2	32.8	54.4	5,000	30.5	2.73

Dominant height is the mean height of the largest 100 trees per hectare, and site index is the dominant height at base age 10 years estimated with Globulus 3.0 model (Tomé *et al.*, 2006).

Comparison of estimates of total stand biomass obtained using tree allometric equations, a constant BEF or the BEF equation

An independent dataset was used to compare estimates of total stand biomass that were obtained using tree allometric equations, a constant BEF or the BEF prediction equation. The dataset contains data from continuous forest inventory and from permanent plots of two other Portuguese pulp companies (Oliveira, 2008).

All plots were located in pure, even-aged eucalyptus plantations. The size of the plot, stand age, dominant height and diameter at breast height (dbh) of trees greater than 5 cm were available from each plot and measurement. In permanent plots, a sample of heights was measured. Trees with a dbh smaller than 5 cm were counted. All live trees in the plots were included in the calculations, and a mean dbh of 3.5 cm was assumed for trees with a dbh less than 5 cm. Table 3 presents the characteristics of the dataset.

Methods

Development of an equation for the estimation of stand root biomass

There are no published studies describing the estimation of root biomass in Portuguese eucalyptus plantations.

Based on published data (Fabião *et al.*, 1995), a relationship between root biomass and aboveground biomass at the stand level was developed. Both linear and non-linear equations were tested. The equation selection procedure was based not only on modeling efficiency (as a measure of fitting quality parameter) but also on the behavior of an equation for ages beyond the range of the fitting dataset. Model efficiency (ME) was computed as

$$ME = 1 - \frac{\sum_{i=1}^{n}(y_i - \widehat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \overline{y})^2}$$

where n is the number of observations in the fitting dataset; y_i and $\widehat{y}_i$ are the observed and the estimated value for observation i, respectively; and $\overline{y}$ is the mean of the observed values.

The ME provides a simple index of performance on a relative scale, where 1 indicates a perfect fit, 0 indicates the equation is no better than a simple average and negative values indicate a very poor equation (Vanclay and Skovsgaard, 1997).

Changes in BEF with stand characteristics

The dependency of BEF on site index, dominant height, stand age, stand density and stand volume was

Table 3. Characterization of the stands used to compare total stand biomass estimates obtained with different approaches (number of observations = 4,819)

	Age (yrs)	Dominant height (m)	Basal area (m²ha⁻¹)	Stand density (ha⁻¹)	Site index (m)	BEF (Mg m⁻³)
Minimum	3.3	5.3	0.6	225	8.6	0.66
Mean	8.3	17.0	11.5	1,156	19.2	0.71
Maximum	18.8	32.4	35.8	3,968	32.4	2.18

Dominant height is the mean height of the largest 100 trees per hectare, and site index is the dominant height at base age 10 years estimated with Globulus 3.0 model (Tomé *et al.*, 2006).

graphically analyzed. The analysis of the graphs allowed the selection of the variables to be used as predictors in the equation for BEF prediction as well as the shape of the relationship.

Total stand biomass (W, Mg ha^{-1}) was defined as the sum of stand aboveground biomass (Wa, Mg ha^{-1}) and stand root biomass (Wr, Mg ha^{-1}). Stand aboveground biomass was defined as the sum of the aboveground biomass of all live trees (n) in the plot expanded for the hectare:

$$W = Wa + Wr = \frac{10,000}{\text{plot area}} \sum_{i=1}^{n} wa_i + Wr$$

where wa_i is the aboveground biomass of the tree i. Wr is estimated with the equation developed in this work.

A system of compatible allometric equations to estimate aboveground biomass for tree components (António *et al.*, 2007) was used for the tree aboveground biomass estimation. This system of equations was based on data from 441 felled trees, collected in several sites (99 plots in high forest and 14 plots in coppiced stands) representative of the eucalyptus expansion area in Portugal. Tree components included wood, bark, live leaves and live branches. The total tree aboveground biomass was calculated as the sum of the tree components. Crown length, used as an independent variable in the biomass equations for the leaves and the live branches, was estimated according to Soares and Tomé (2001).

Stand volume was defined as the sum of total tree volume, which was estimated according to Tomé *et al.* (2001) and expanded for the hectare. A height-diameter equation (Soares and Tomé, 2002) was used to estimate tree height in trees for which this variable was not available.

In this paper, the biomass expansion factor (BEF, Mg m^{-3}) was defined as the ratio of the total stand biomass (aboveground biomass plus root biomass, dry weight, Mg ha^{-1}) to the stand volume with bark (m^3 ha^{-1}).

Development of an equation to estimate BEF

The analysis of the graphs relating BEF and stand variables indicated which variables should be used in an equation for BEF prediction. The equation was fitted using non-linear regression techniques and the PROC NLIN procedure of SAS version 9.1 (SAS Institute Inc., 2004). Model fitting was assessed with ME, as described above. Regression assumptions, i.e., homo-

scedasticity and normality of the model errors, were tested using plots of studentized residuals over predicted values and QQ-plots, respectively. Weighted regression was used to correct heteroscedasticity (Myers, 1986). Weights were found using the methodology described by Parresol (1999). Non-normality of the errors was overcome by using iteratively reweighted least squares regression with the Huber function, as an influence function for reducing the influence of data points containing large errors on fit (Myers, 1986).

Comparison of estimates of total stand biomass obtained using tree allometric equations, a constant BEF or the BEF equation

Total stand biomass estimation in which stand aboveground biomass is determined using tree allometric equations (functions of dbh and total tree height or tree crown length) is considered the most accurate estimation methods for biomass (IPCC, 2003; Jalkanen *et al.*, 2005; Zianis *et al.*, 2005). The biomass values obtained using this method were compared with estimates of biomass obtained using a) the constant BEF of 0.77, used in the PNIR on Greenhouse Gases 1990-2008 (Pereira *et al.*, 2010), or b) the BEF prediction equation dependent on stand variables, described above.

Stand biomass estimates obtained using tree allometric equations (António *et al.*, 2007) were assumed to be more accurate than those obtained using a constant BEF or the BEF prediction equation.

To compare different estimates of total stand biomass, those obtained with a system of tree allometric equations (stand aboveground biomass plus stand root biomass) were plotted against those obtained using a constant BEF and those obtained using the BEF prediction equation. The evolution of the error by dominant height class was analyzed. Error (error), percent error (%error) and total percent error (T%error) were defined as

$$error_C = W_{EQ} - W_{BEF\_C}$$
$$error_E = W_{EQ} - W_{BEF\_E}$$

and

$$\%error_C = \frac{W_{EQ} - W_{BEF\_C}}{W_{EQ}} 100$$

$$\%error_E = \frac{W_{EQ} - W_{BEF\_E}}{W_{EQ}} 100$$

and

$$T\%error_C = \frac{\sum W_{EQ} - \sum W_{BEF\_C}}{\sum W_{EQ}} \; 100$$

$$T\%error_E = \frac{\sum W_{EQ} - \sum W_{BEF\_E}}{\sum W_{EQ}}$$

where W_{EQ} is the total stand biomass in which stand aboveground biomass was estimated using tree allometric equations, W_{BEF_C} is the total stand biomass estimated with a constant BEF, and W_{BEF_E} is the total stand biomass estimated with the BEF prediction equation developed in the present study. For W_{EQ}, stand root biomass is also estimated with equations developed in the present study.

Results

Stand root biomass estimation

Figure 1 shows the relationship between stand root biomass and stand aboveground biomass from the data available for *E. globulus* in Portugal. Three functions were fitted to model this relationship:

1 – linear relationship with the Portuguese data

The relationship is approximately linear, but data taken at two years fall below the line. As frequently described in the literature, root biomass (Wr, Mg ha^{-1}) is first estimated as a no-intercept linear equation of aboveground biomass (Wa, Mg ha^{-1}) and expressed as a root:shoot ratio (Klepper, 1991):

$$Wr = 0.2487 \; Wa \; <=> \; \frac{Wr}{Wa} = 0.2487 \quad (R_{adj}^2 = 0.981)$$

2 – non-linear relationship with the Portuguese data

Taking into account the graphical form observed in Figure 1, a non-linear equation was also fitted:

$$Wr = \frac{46.6193}{\left(1 + e^{-0.0216Wa}\right)^{1/0.1786}} \quad (ME = 0.958)$$

3 – non-linear relationship with the Portuguese data and data from the literature

The previous estimates obtained were compared with the following results obtained by Resh *et al.* (2003) in an *E. globulus* stand in Tasmania: Wa = 248.3 Mg ha^{-1} and Wr = 73.8 Mg ha^{-1} (stands with 10 years). Our Wr estimates, for ages near the final cut, seemed high when the linear equation was used and low when the non-linear equation was used. To address this inconsistency, the non-linear equation was fitted again with the same dataset but now incorporated the data point from the literature (248.3, 73.8). The result was as follows:

$$Wr = \frac{99.6231}{\left(1 + e^{-0.0116Wa}\right)^{1/0.1769}} \quad (ME = 0.974)$$

Changes in BEF with stand characteristics

Figure 2 presents the relationship between BEF and the following stand characteristics: site index, dominant height, stand age, stand density and stand volume. BEF values begin at a high level and decrease exponentially as stand age, dominant height, stand volume and basal area increase. BEF values eventually become relatively constant close to 0.72. The constant BEF used in the PNIR (0.77) therefore represents a slight overestimation of total biomass for young stands, as can be seen in Figure 2.

Development of an equation to estimate BEF

Based on the graphical relationships previously observed between BEF and the stand variables, the rectangular hyperbole function was chosen as a segmented model to estimate BEF:

$$\begin{cases} BEF = \dfrac{X}{\alpha + \beta \, X}, \text{ if } X < X_0 \\[2mm] BEF = \dfrac{X_0}{\alpha + \beta \, X_0} = constant, \text{ if } X \geq X_0 \end{cases}$$
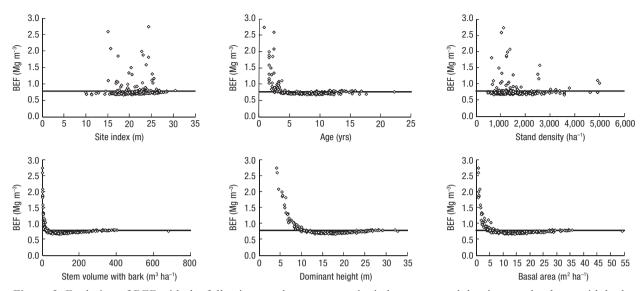
where X is a stand variable, and α, β and X_0 are estimated parameters.

Age, dominant height and stand volume with bark were each tested as the predictor stand variable (X). Basal area was excluded because dbh cannot be measured in young trees with a height less than 1.30 m.

The best model used dominant height as the predictor stand variable (ME = 0.894):

$$\begin{cases} BEF = \dfrac{hdom}{-6.2153 + 1.8406 \, hdom} & \text{if } hdom < 13.6 \\[3mm] BEF = 0.7225 & \text{if } hdom \geq 13.6 \end{cases}$$
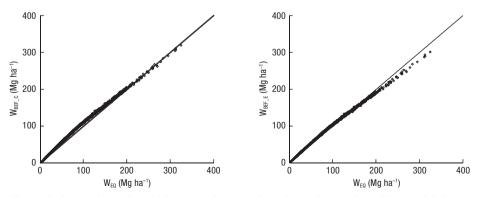
where hdom is dominant height (m).

Figure 2. Evolution of BEF with the following stand parameters: site index, age, stand density, stand volume with bark, dominant height and basal area; the horizontal line represents a constant BEF (0.77) used in the PNIR on Greenhouse Gases (Pereira *et al.,* 2010).
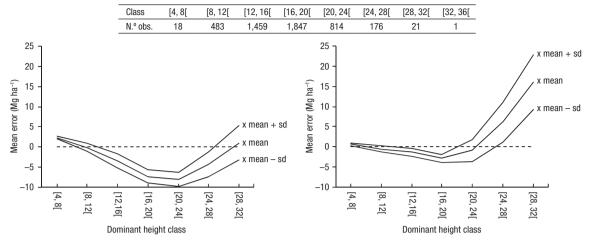
Comparison of estimates of total stand biomass obtained using tree allometric equations, a constant BEF or the BEF equation

Figure 3 shows the comparison of total stand biomass when stand aboveground biomass was based on tree allometric equations, a constant BEF or a BEF estimated with the equation described above. Compared with total stand biomass estimates based on allometric equations, a constant BEF results in overestimations of total stand biomass (mean error = $-$ 5.4 Mg ha^{-1}). The equation proposed in this study, which uses dominant height as the predictor stand variable, also overestimates total stand biomass, but to a lesser extent (mean error = $-$ 1.5 Mg ha^{-1}). On the other hand, an underestimation of total stand biomass was observed

for large values of total stand biomass when the equation was used for estimating BEF, although errors greater than 5 Mg ha^{-1}, corresponding to a mean total stand biomass of 196 Mg ha^{-1}, were observed for only a small percentage of the whole dataset (3%).
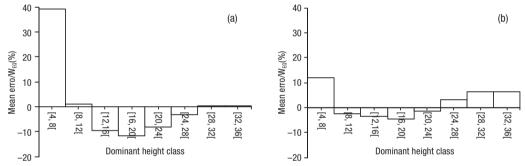
Greater values of mean error were obtained when a constant BEF was applied in stands with a dominant height between 16 and 24 m (Figure 4), corresponding to a percent mean error of 9.9% of the total stand biomass (Figure 5). A small error obtained for class [4, 8] corresponds, however, to a percent mean error of 40% (Figure 5). BEFs estimated with the proposed equation were associated with large errors only in stands with a dominant height between 24 and 32 m (Figure 4), corresponding to a percent mean error of 4.7% of the total stand biomass (Figure 5).

Figure 3. Comparison of total biomass estimates using allometric equations (W$_{EQ}$) and (left) estimates using a constant BEF (W$_{BEF\_C}$) or (right) estimates using a BEF prediction equation (W$_{BEF\_E}$).

Class	[4, 8[	[8, 12[	[12, 16[	[16, 20[	[20, 24[	[24, 28[	[28, 32[	[32, 36[
N.º obs.	18	483	1,459	1,847	814	176	21	1

Figure 4. Mean error by dominant height class; x mean is the mean value of the error, and sd is the standard deviation. (a) Differences between total biomass estimates using individual tree allometric equations and estimates using a constant BEF; (b) Differences between total biomass estimates using individual tree allometric equations and estimates using the proposed BEF equation.

Figure 5. Mean error as a percentage of mean total stand biomass estimated with the individual tree allometric equations, given for each dominant height class. (a) Differences between total biomass estimated with the allometric equations and with a constant BEF; (b) Differences between total biomass estimated with the individual tree allometric equations and with the proposed BEF equation.

In the dataset used, the total percent errors of biomass are 8.7% (T%error$_C$) and 2.3% (T%error$_E$).

Discussion

Using the linear equation selected to estimate stand root biomass, the value 0.2487 for the Wr/Wa ratio is within the range of values reported by Cairns *et al.* (1997) for angiosperm tree types (0.13 – 0.37). However, there is no consensus on the linear relationship between Wa and Wr. Several studies have indicated that Wr/Wa varies with stand age (a conclusion confirmed by our data; see Fig. 1) and is a function of tree species and tree type (angiosperms and gymnosperms) (several examples in Cairns *et al.*, 1997). Some authors emphasize a decrease in relative root biomass within

the first few decades after stand establishment, followed by a stable constant ratio (e.g. Peichl and Arain, 2007; Tobin and Nieuwenhuis, 2007). Eucalyptus data show a decrease in the Wr/Wa ratio when measurements at one and two years are analyzed and an increase when measurements at two years and six years are compared (Fig. 1). Apparently, an initial investment in the root system, at one year of age, is gradually transferred, during stand development, to branches and leaves in the crown and later returned to the root system. Root data at six years was only obtained in block 2 of the trial. The values reported for the other ages represent the mean of the two blocks.

The data suggest that during the period from age two to age six, maintenance of the tissues produced and growth in a fast growing species can be attributed to biomass allocation to the root system, in a site with a

Mediterranean climate with maritime influence, where a dry season (usually from May to September) is very pronounced.

The non-linear equation developed with the Portuguese data has the advantage of having an asymptote that limits the value of Wr. The maximum value of Wa in the dataset used to fit the equation was only 157.4 Mg ha⁻¹ and was observed in the fertilized and irrigated plots containing six-year-old trees. However, a Wa of 432 Mg ha⁻¹ has been observed for 22-year-old Portuguese eucalyptus stands (unpublished data). For this Wa value, linear and non-linear equations estimate Wr values of 107.4 and 46.6 Mg ha⁻¹, respectively.

The use of information from Resh *et al.* (2003) produced a higher asymptote value and, consequently, more realistic estimates of Wr. Nevertheless, results obtained using this equation are similar to those using the linear equation for the range of Wa analyzed. Differences in Wr estimates are more evident for values of Wa greater than 370 Mg ha⁻¹. From a biological point of view, the selection of an asymptote equation is therefore more realistic.

It is evident from this analysis that more data for root biomass are required to support these or other conclusions. In particular, data for stand ages beyond 6 years are needed to confirm the trend of eventual stabilization. Previous studies with eucalyptus in Portugal (Fabião *et al.*, 1987) concluded that the amount and distribution of root biomass within the soil profile was strongly dependent on soil texture and the availability of water and nutrients. A dataset covering different soil and climatic conditions is needed to define an equation that can be more reliably used for extrapolation. Additionally, there is no information about root biomass in coppice systems. After harvesting stands regenerated from seedlings, root systems are already established and the Wr/Wa ratio, at least in the early phase of stand development, would certainly not be equal to the values presented in this work. Therefore, the equation must be used carefully when applied to coppice stands.

The trend observed between BEF and stand age has also been observed in other species (e.g. Brown, 2002; Jalkanen *et al.*, 2005; Lehtonen *et al.*, 2007; Tobin and Nieuwenhuis, 2007). These reports support the findings concerning resource allocation during the growth process: initially low values of stem biomass, resulting from a biomass increase in the root system and leaves in the crown, followed by increased resource allocation

to the stem biomass. Furthermore, BEF values were not correlated with site index or stand density.

The segmented model that was fitted to estimate BEF in Portuguese eucalyptus stands is in agreement with the findings of António *et al.* (2007), which focused on the development of individual tree allometric equations. They found that expressing at least one parameter of the equations as a function of dominant height increased the precision of the estimates. Thus, the biomass estimates were dependent on stand development. It is important to note that this equation is not applicable to very young stands (hdom < 3.4 m), as it will produce negative predictions (the range of dominant height in the fitting dataset was 3.4-32.8 m). However, in a *E. globulus* database with more than 20,000 stand observations from forest inventory, permanent plots and trial measurements, only 13 cases represent dominant heights smaller than 3.4 m. In these stands (measurements), the quadratic mean dbh ranged between 0.8 and 2.2 cm. In forest inventories, only trees larger than 5 cm of dbh are typically measured. The probability of having a stand with a dominant height less than 3.4 m is therefore quite small.

Conclusions

In order to improve *E. globulus* Portuguese biomass estimates in accordance with IPCC Good Practice Guidance, we propose the use of the BEF prediction model described in this work:

$$\begin{cases} BEF = \dfrac{hdom}{-6.2153 + 1.8406\, hdom} & \text{if } hdom < 13.6 \\ \\ BEF = 0.7225 & \text{if } hdom \geq 13.6 \end{cases}$$

where hdom is dominant height (m).

This model should produce less biased and more accurate biomass estimates than constant BEFs because they account for variation in the allometry of the trees based on stand development.

Acknowledgements

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