

Biomass allometry and carbon factors for a Mediterranean pine (*Pinus pinea* L.) in Portugal

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Abstract

Forests play an important role in the global carbon balance because they offset a large portion of the carbon dioxide emitted through human activities. Accurate estimates are necessary for national reporting of greenhouse gas inventories, carbon credit trading and forest carbon management but in Portugal reliable and accessible forest carbon measurement methodologies are still lacking for some species. The objective of this study was to provide forest managers with a comprehensive database of carbon factors and equations that allows estimating stand-level carbon stocks in *Pinus pinea* L. (*P. pinea*), regardless of the tree inventory information available. We produced aboveground biomass and stem volume equations, biomass expansion factors (BEF) by component as well as wood basic density (WBD) and component carbon fraction in biomass. A root-to-shoot ratio is also presented using data from trees in which the root system was completely excavated. We harvested 53 trees in centre and south Portugal covering different sizes (6.5 to 56.3 cm), ages (10 to 45 years) and stand densities (20 to 580 trees ha⁻¹). The results indicate that aboveground allometry in *P. pinea* is not comparable with other pines and varies considerably with stand characteristics, highlighting the need to develop stand-dependent factors and equations for local or regional carbon calculations. BEF_{aboveground} decreases from open (1.33 ± 0.03 Mg m⁻³) to closed stands (1.07 ± 0.01 Mg m⁻³) due to a change in biomass allocation pattern from stem to branches. Average WBD was 0.50 ± 0.01 Mg m⁻³ but varies with tree dimensions and the root-to-shoot ratio found was 0.30 ± 0.03. The carbon fraction was statistically different from the commonly used 0.5 factor for some biomass components. The equations and factors produced allow evaluating carbon stocks in *P. pinea* stands in Portugal, contributing to a more accurate estimation of carbon sequestered by this forest type.

Key words: *Pinus pinea*; carbon balance; climate change; biomass inventory.

Resumen

Alometría de la biomasa y factores de carbono para un pino Mediterráneo (*Pinus pinea* L.) en Portugal

Los bosques juegan un papel importante en el balance global del carbono porque desplazan una gran porción del dióxido de carbono emitidos por actividades humanas. Se necesitan estimaciones precisas para los informes nacionales de los inventarios de los gases de efecto invernadero, mercados de créditos de carbono, y manejo de carbono en los bosques. Pero en Portugal todavía faltan, para algunas especies, metodologías de mediciones fiables y accesibles de carbono en los bosques. El objetivo de este estudio es proporcionar a los gestores forestales una base de datos completa de los factores y ecuaciones del carbono que permitan estimar los stocks de carbono a nivel de rodal, en *Pinus pinea*, independientemente de la información disponible de los inventarios de árbol. Producimos ecuaciones de biomasa del matorral, y del volumen del troco, factores de expansión de biomasa (BEF) por componente así como densidad básica de la madera (WBD) y fracción de los componentes de carbono en la biomasa. Un ratio raíz-tallo se presenta también utilizando datos de los arboles en los que los sistemas radicales se extrajeron completamente. Se cosecharon 53 árboles en el centro y sur de Portugal, cubriendo tamaños diferentes (6,5 a 56,3 cm), edades (10 a 45 años), y densidad del rodal (20 a 580 árboles ha⁻¹). Los resultados indican que la alometría del sistema radical en *P. pinea* no es comparable con otros pinos y varía considerablemente con las características del rodal destacando la necesidad de desarrollar factores dependientes del rodal y ecuaciones para cálculos de carbono a nivel local o regional. BEF_{radical} disminuye de rodales abiertos (1,33 ± 0,03 Mg m⁻³) a cerrados (1,07 ± 0,01 Mg m⁻³) debido a cambios en la asignación de biomasa de tronco a ramas. La media de WBD es 0,50 ± 0,01 Mg m⁻³ pero varía con la dimensión de los

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árboles y el ratio de raíz a tallo se encuentra entre $0,30 \pm 0,03$. La fracción de carbono fue estadísticamente diferente del factor comúnmente utilizado de 0,5 de algunos componentes de biomasa. Las ecuaciones y los factores producidos permiten la evaluación de los stocks de carbono en rodales de *P. pinea* en Portugal, contribuyendo a una información más precisa del carbono secuestrado por este tipo de bosque.

Palabras clave: *Pinus pinea*; balance de carbono; cambio climático; inventario de biomasa.

Introduction

Reliable estimates of forest carbon stocks and changes over time are necessary to understand the global carbon cycle and to know to what extent they contribute to mitigate greenhouse gas emissions. Feasible and comprehensive carbon estimates in forests are important under international commitments as the Kyoto Protocol or the United Nations Framework convention on Climate Change but also because there is a growing interest of enterprises and landowners in getting involved in the market opportunities available for forest carbon offset credits (Hamilton *et al.*, 2007). The quantification, reporting and verification of carbon sequestered by forests are frequently not as transparent as it should and this has major implications on policy decisions regarding forest conservation and management (Clark *et al.*, 2001).

Methods to assess carbon stock at stand level

Inventory-based methods are the most common for assessing forest carbon stock and changes. IPCC (2003) suggests that this can be done either by directly applying allometric models that predict tree biomass components based on field measurements of individual trees (like diameter at 1.30 m or tree height), or using multiplication factors that allow to convert or expand stem volume to the tree biomass component wanted. This involves the development of site-specific allometric equations requiring tree harvesting and weighting in the field, which is expensive and time-consuming. The use of existing equations comes as an alternative but potential intersite variation in wood quality and biomass allocation throughout stand maturity may introduce errors in the final estimates (Lehtonen *et al.*, 2004). Biomass expansion factors (BEF) and/or conversion factors (CF) are the most widely used methods for biomass calculations because they readily convert, in only one step, stand volume estimates (usually available in forest inventories) in biomass or carbon. Both are multiplication factors but BEF allows to expand

growing stock volume to whole or merchantable biomass components of the stand (*e.g.* crown) while CF includes wood basic density (WBD) and carbon fraction conversions. Multiplication factors, foreseen by IPCC Good Practice Guidelines in the case where no biomass information is available, can be species-specific or represent broad species groups (see review in Somogyi *et al.*, 2006). As is the case for generic allometric equations, they do not account for intersite variability and the matching to the site under study requires previous measurements and tree harvesting. According to IPCC (2003), the uncertainty on using generic BEF, WBD and root-to-shoot ratios is considered to be about 30% but Ravindranath and Ostwald (2008), for example, state that the use of generic factors may produce misleading estimates with errors as large as 70%. In spite of the growing number on allometric relationships and expansion factors, ecosystem specific studies continue to be important because they help to reduce this uncertainty.

Pinus pinea overview

In this paper we studied an emblematic Mediterranean species – pinion or umbrella pine (*Pinus pinea* L.), a native pine of Southern Europe covering about 650,000 ha of the Mediterranean Basin (Quézel and Médail, 2003). The major interest of this species in Portugal is the production of edible nuts, and for that stands must be managed in a way to reach a maximum of 100 trees ha⁻¹ at the mature phase which occurs around 30 years old. Even with a large inter-annual cone production variability, which depends on the climatic conditions during the 4 years cone development period, *P. pinea* provides higher incomes to owners because pine seeds are highly prized in the international markets, much more than other forest resources (*e.g.* timber) (Mutke *et al.*, 2005b). Other distinctive characteristic of the species is its genetic uniformity (Vendramin *et al.*, 2008) combined with a high level of phenotypic plasticity (Mutke *et al.*, 2005a). In fact *P. pinea* appears either in arid inland or coastal sea areas affected by salinity stress, and can potentially help mitigating

desertification problems in these particular areas. Drought tolerant species from Mediterranean regions like *P. pinea* may be interesting in a climate change scenario because they are naturally adapted to warmer climates and to water stress. Future scenarios of vegetation distribution predict that these species may shift towards higher latitudes due to climate change (Benito Garzon *et al.*, 2008; Ohlemuller *et al.*, 2006) and turn out to be potentially interesting in future afforestation/reforestation programs in regions becoming susceptible to droughts. *P. pinea* stands managed in long rotations and with moderate wood productivity may also sequester large carbon stocks and contribute to mitigate greenhouse gas emissions. A carbon sequestration simulation made by Del Rio *et al.* (2008) using an integrated single tree model (PINEA2) in even and uneven aged *P. pinea* stands over a 100-year period, estimated 1.2 to 1.5 Mg of carbon sequestered per ha and per year ($\text{MgC ha}^{-1} \text{ year}^{-1}$). These values are underestimated since carbon accumulated in the soil was not accounted, only the annual tree growth and cone production.

The main objective of this paper is to provide the tools to help stakeholders in quantifying carbon stocks for *P. pinea* at stand level, regardless of the inventory information available for the site, and that can either be used for national quantifications, local studies as an alternative to the existing factors that revealed inappropriate. Biomass and volume allometric equations, biomass expansion factors, biomass and carbon conversion factors were developed for the species using destructive tree sampling.

Material and methods

Stand description, climate and vegetation

P. pinea in Portugal covers 3% of total forest area (83,900 ha) but the area had grown 10% in the last 10 years (Tomé *et al.*, 2007). Although occurring throughout the country, most of the area is located in the south where climate and soil allows higher commercial cone yield. The 17 stands used for the selection of the trees for destructive sampling are located in center and south Portugal (Fig. 1) covering most of the *P. pinea* distribution in Portugal. The climate is Mediterranean with a hot and dry summer, with a mean annual temperature of 16°C. Average annual precipitation (1961-1990) varies slightly between stands ranging from 572

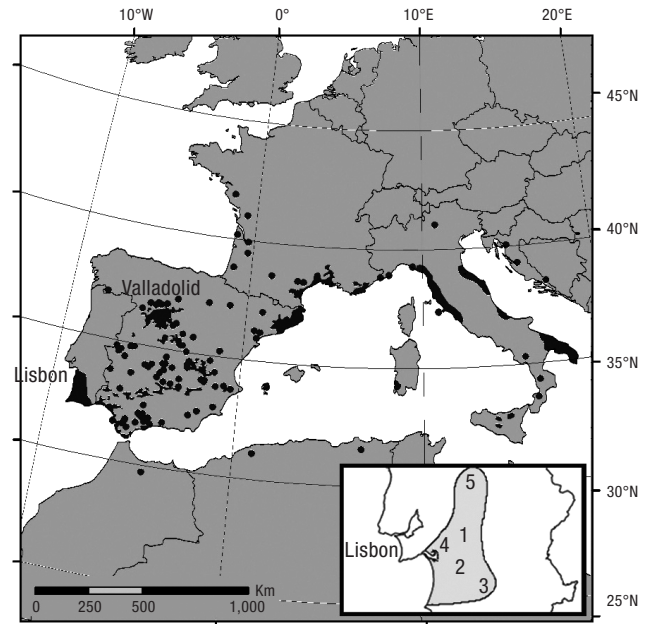


Figure 1. *Pinus pinea* distribution in Europe in 2008. Picture adapted from Fady *et al.* (2004). The box in the right represents the location of the stands used for biomass harvesting in Portugal (in correspondence with the numbering from Table 1); the light gray represents the geographical area of the 101 pure plots inventoried.

to 735 mm with more than 80% occurring between October and April.

Stands are pure, except in one site (Pegões) in which *P. pinea* is mixed with cork oak or maritime pine. The understory consists of grazed pastures with annual C3 herbaceous plants and, in some stands, dispersed shrubs of *Ulex* and *Cistus*. Soil types ranged from sand, loamy sand and sandy loam textures, derived from sand stones sedimentary rocks. All of them are nutrient poor. The stand density ranged from 20 to 580 trees ha^{-1} and LAI ranged from 1.5 to 11, calculated as the sum of all side needle area in the plot (m^2) to the plot area (m^2) (Table 1).

Sample tree selection

A total of 53 *P. pinea* trees were harvested for biomass, stem volume, wood basic density and carbon in biomass analysis. The sampling was stratified by 5 cm diameter at breast height from 5 to 60 cm. Stem diameter at breast height (1.30 m) (d), tree height (h), height to the crown base (hc), crown radius (cr) were measured in each tree. Stand variables were subsequently calculated, namely stand density (N), stand basal area (G) and dominant height (hdom) (Table 1).

Table 1. Characteristics of the sites used for harvesting

| Location | Lat(N)/ Long(W) | T (°C) | pp (mm) | Plots, trees W, trees V | Stand characteristics (min-max) | | | | | Trees harvested (min-max) | | | |
|-----------------------------|------------------------|-----------|------------|-------------------------------|--|-------------|--------------------------------|---|--------------|---------------------------|-----------|-----------|-----------|
| | | | | | LAI (m ² m ⁻²) | hdom (m) | N (trees ha ⁻¹) | G (m ² ha ⁻¹) | Stand age | d (cm) | h (m) | hc (m) | cw (m) |
| (1) Pegões | 38°37'67" -8°37'36" | 15.9 | 709 | 6, 15, 33 | 3.3-5.3 | 13.9-18.1 | 60-207 | 10.1-15.3 | 40 | 8.0-56.3 | 3.7-17.3 | 2.2-10.0 | 1.4-5.1 |
| (2) Palma | 38°28'07" -8°38'40" | 16 | 572 | 2, 5, 5 | 4.1, 4.2 | 14.6, 18.1 | 110, 130 | 20.1, 20.7 | 45 | 29.4-43.2 | 11.0-12.0 | 2.2-4.3 | 4.1-5.4 |
| (3) Ferreira do Alentejo | 38°08'29" -8°18'18" | 16.2 | 586 | 2, 4, 4 | 2.5, 2.8 | 10.9, 15.0 | 74, 170 | 7.7, 8.4 | 40 | 9.2-30.9 | 2.7-10.1 | 0.9-6.2 | 1.3-6.8 |
| (4) Gâmbia | 38°33'17" -8°47'30" | 16.1 | 735 | 1, 10, 5 | 11 | 6.6 | 580 | 14.6 | 13 | 7.5-20.4 | 2.6-5.9 | 0.9-1.9 | 1.1-2.2 |
| (5) Coruche | 38°57'34" -8°25'45" | 16 | 642 | 6, 6, 6 including roots | 1.5-4.9 | 5.3-11.4 | 20-120 | 1.5-7.5 | 20 | 6.5-46.0 | 2.1-7.7 | 0-1.6 | 1.2-4.7 |

Climate: T, mean annual temperature (°C); pp, total annual precipitation (mm). Stand characteristics: Plots, number of plots inventoried in the stand; trees W, number of trees harvested for biomass; trees V, number of trees used for volume; LAI, leaf area index (m² m⁻²); hdom, stand dominant height (m); N, stand density (trees ha⁻¹); G, stand basal area (m² ha⁻¹); Stand ag, of the stands. Characteristics of the trees harvested: d, diameter at breast height (cm); h, tree height (m); hc, height to the crown base (m); cw, crown radius (m). Minimum and maximum values separated by dashes.

Aboveground biomass sampling

The main aboveground biomass components—stem wood, stem bark, branches and needles—were weight in 40 trees by harvesting and additionally other 13 where measured for volume calculations. Due to limited economic resources, the root biomass was weight by the excavation method in 6 of them. In some trees the cones had already been harvested (the harvesting period in Portugal is between 15th December and 31st March) so cones were not used in the models. In fact, due to the importance of cone production, there are specific models already available to predict cone weight in the country (Freire, 2009). Trees were cut from the stump, and dead and living branches were separated from the stem. The stem wood identification inside the crown was sometimes difficult, since trees tend to produce bifurcations due to the lack of apical dominance. In these cases, the most vigorous branch was selected to represent this stem fraction. The stem was then fractioned in 2 m width logs (in small trees every 1 m) and weighted in the field. A disk was collected from the base of each log and weighted in the field and kept for laboratory determination of dry weight and for stem wood/bark proportion calculations. The cross diameters of the disks with and without bark were measured in fresh conditions for volume calculations. A systematic sampling approach was used to collect at least 20% of the

crown biomass choosing the 1st branch in each group of 5 starting from the base to the tip of the crown, for wood and needle separation. The remaining crown was weight in the field but without any component separation. Branches were divided in 3 diameter classes: less than 2.5 cm, between 2.5 and 7 cm and more than 7 cm and these fractions weight. Portable digital scales with 1 g precision were used for field weightings. For each tree component a sample of approximately 200-500 g was kept and sealed in labeled plastic bags for laboratory determination of dry weight. The biomass of each component was calculated by the product of dry weight to fresh weight ratio of the component sample and the total fresh weight of the component in the tree, estimated by the proportion of the component in the total fresh weight (Porté *et al.*, 2002; Ritson and Sochacki, 2003).

For tree volume we summed the volume calculated for each intermediate log with the Smalian formula assuming a cylinder geometric shape for the stump and intermediate logs and a cone geometric shape for the top log. On average, the separation and weighting of each tree took 2 hours with the work of 5 persons but the time spent in aboveground biomass separation varied according to the tree dimensions: the maximum was 5 hours with 7 persons for a tree with 3.5 Mg (fresh weight) and the minimum was 1 hour with 5 persons for a tree with 0.035 Mg (fresh weight).

Root sampling

Six trees were used for root biomass determination using the excavation method. The trees were selected from stands with different soil types within the same area (Regosol, Cambisol and Luvisol) (FAO, 1998) and with different, yet low, stand densities (Table 1). After cutting the tree from the stump, a geometric polygon was identified on the ground taking into account crown projection and/or half the distance to neighborhood trees. The stump and the soil within the marked area were removed with a hydraulic excavator, and roots were separated in piles according to soil horizons and depths. The maximum depth excavated varied between 1 and 2 m according to the depth of the sandstone rock and the root system development of the tree. In each pile, roots were manually separated, washed to remove soil particles and exposed to open air to dry. The same procedure was used for the stump. Roots were separated in 3 diameter classes: less than 5 mm (fine), between 5 and 30 mm (small) and more than 30 mm (coarse), and then weighted in the field. Portable digital scales with 1 g precision were used for field weightings. For each tree component, two samples were collected and sealed in labeled plastic bags for dry weight and carbon analysis. All the samples were oven-dried to constant weight at 70°C for dry weight calculations. The total dry biomass for each component was estimated from fresh weight based on sample dry weights.

Biomass and volume equations

The allometric relationship between tree biomass (or volume) and tree or stand variables usually takes the form of a power function and has been widely studied (see review in Zianis *et al.*, 2005). In this study we tested the following power functions: $w = k_i x^a$ and $w = k_i x^a y^b$, where w is the dependent variable that can be either biomass or volume, where k , a and b are parameters to be estimated by regression analysis and x and y are tree variables. The tree variables tested were: d (stem diameter at 1.3 m), h (tree height), h_c (height to the crown base), cr (crown radius) and the slenderness index (h/d).

Sapwood area was also tested as a candidate explanatory variable. For sapwood area calculation, the surface of the disk measured at the base of the living crown was sanded on one side and then scanned on a flatbed scanner. Sapwood area and the number of rings in each disk were measured in 4 perpendicular

directions using the software WindENDRO (Regent Instruments, Sainte-Foy, Quebec, Canada). Sapwood area was only used to predict needle biomass in an independent model (following the methodology described above), since only 32 out of the 40 trees sampled for biomass had this measured done. These equations were built because the relationship between needle biomass (and area) to sapwood area is closely linked with plant productivity (Ryu *et al.*, 2010) and is a common variable in carbon balance models based in the pipe-model theory (Waring *et al.*, 1982). This theory proposes that a given unit of leaf (biomass) area is supplied with water from a constant quantity of conducting pipes and can help explain some biomass patterns in *P. pinea* trees with stand development.

For each component (volume with bark, stem bark, stem wood, branches and needles), the non-linear models were fitted by the least squares method, using all possible combinations of variables. The root biomass was not included in the simultaneous fit because only 6 trees were used. The performance of the biomass components models was evaluated based on the Press residuals (r_p) (Myers, 1990) guaranteeing the significance of all the parameters in the selected models. The normality of the model errors was evaluated by plotting the studentized residuals over the normal residuals (QQ-plots). The non-normality was overcome in the final model with iteratively reweighted least squares regression using the Huber function to reduce the influence of data containing large errors (Myers, 1990). To overcome heterocedasticity, the models were fitted with weighted non-linear regression, using Parresol (1999) methodology to calculate the weights. Models were evaluated using the methodology proposed by Soares *et al.* (1995) and Vanclay and Skovsgaard (1997), which consists of calculating the following statistics based on the PRESS residuals (r_{pi}):

- 1) Model efficiency ($M_{\text{efficiency}}$) computed as:

$$M_{\text{efficiency}} = 1 - \frac{\sum_{i=1}^n r_{pi}^2}{\sum_{i=1}^n (y_i - \bar{y})^2}$$

where r_{pi} is the Press residual from tree i (residual obtained when tree i is not included in the fit) for the dependent variable, \bar{y} is the average value and n is the number of trees measured;

- 2) model bias (M_{bias}), expressed by the r_p average;
- 3) model precision ($M_{\text{precision}}$) expressed by the average of the absolute values of r_p . The best models

were the ones with higher efficiency and lower bias and precision values. The models selected for each tree biomass component (except the root component), including total tree aboveground biomass expressed as the sum of the biomass components, were simultaneously fitted with the non-linear seemingly unrelated regression (Parresol, 1999; 2001). Model fittings were performed with SAS software (SAS, 2004).

The aboveground biomass measured in the 40 trees harvested was correlated with the estimates obtained with a set of biomass equations from Spanish *P. pinea* stands (Fig. 1) developed by Montero *et al.* (2005) and the results are presented in Table 3. These consist of 7 biomass equations (for total aboveground, stem, branches of less than 2 cm, between 2 and 7 cm and higher than 7 cm, needles and roots) adjusted with allometric functions using *d* as the independent variable. The data set used 47 trees harvested in the region of Huelva, Valladolid (Spain) (Fig. 1) with *d* ranging from 7.5 cm to 63 cm. No information was provided regarding stand characteristics. The average temperature (12°C) and the annual precipitation (435 mm) (1971-2000) is lower than the sites analyzed in this study probably as a result of the continental influence.

Expansion factors - biomass aboveground and root-to-shoot ratio

To compute BEF_i we used a total of 101 pure *P. pinea* permanent plots selected from a national grid (Freire, 2009) that used the same inventory methodology described in section 2.2 (Table 2). No trees were harvested from these plots, these were only used to compute BEF_i . The subscript index (*i*) refers to needle, branches, stem wood, stem bark, stem (wood + bark), crown (branches + needles) or total aboveground biomass, these last 3 thereafter named aggregated BEF. BEF_i is computed as follows:

$$BEF_i \text{ (Mg m}^{-3}\text{)} = \frac{\text{Biomass}_i \text{ (Mg ha}^{-1}\text{)}}{\text{Volume with bark}_i \text{ (m}^3 \text{ ha}^{-1}\text{)}}$$

Volume with bark and biomass were estimated using equations from Table 3 (presented in the *Results* section). BEF_i values were plotted with stand variables (N, hdom and G) in order to study possible trends in biomass allocation patterns.

The root-to-shoot ratio refers to the roots and stump biomass (Mg) over total aboveground biomass components (branches, needles, stem wood and stem bark) (Mg), and was calculated for the 6 trees in which root biomass was measured.

Conversion factors - Wood basic density (WBD) and Carbon fraction in biomass

WBD is defined here as the ratio of wood biomass (oven-dry matter) (Mg) to the green volume (m^3) and was measured in wood disks (without bark) taken each 2 m (or 1 m long) from the stem. The knots and resin wounds were separated in the disks in order to avoid local data overestimation. The displacement of volume by immersing the wood in water was the method used (Zobel and Buijtenen, 1989). Wood and bark were oven-dried until a constant weight at 60-80°C for dry weight calculations. Tree WBD was calculated by averaging WBD in each disk weighed by the corresponding diameter without bark. The variation of WBD between and within trees was first assessed by graphical analysis. Trees were grouped in 3 height classes (trees from 2 to 6 m, 6 to 10 m and higher than 10 m) and the average WBD (and the corresponding standard error) was calculated at each intermediate height (at the base, 2 m, 4 m, 6 m and so on). A regression analysis was then performed, using tree *d*, *h* and discs height level within the tree, as well as interactions between these variables, as regressors in order to test the significance of the effect of tree size and height level on WBD.

Table 2. Main characteristics of the 101 *Pinus pinea* plots inventoried and used for BEF_i calculations and aboveground biomass calculations

| | N (trees ha ⁻¹) | hdom (m) | G (m ² ha ⁻¹) | V (m ³ ha ⁻¹) | Aboveground biomass (Mg ha ⁻¹) |
|------|--------------------------------|-------------|---|---|--|
| Min | 18 | 4 | 2 | 6 | 7 |
| Mean | 194 | 12 | 10 | 53 | 63 |
| Max | 1647 | 21 | 26 | 175 | 194 |

Table 3. Final models selected for biomass components (in kg) and volume with bark (in m³) considering tree variables as predictors

| | Equation | Average (min-max) | Par. | Estimates | R ² ajd | M _{bias} | M _{precision} | M _{efficiency} |
|----------------------|---|----------------------|------|----------------|--------------------|-------------------|------------------------|-------------------------|
| Needles | k c ^a (h/d) ^b | 38 (3-222) | k | 22.27 (18.09) | 0.71 (0.83) | 2.68 (0.97) | 11.56 (5.05) | 0.63 (0.82) |
| | | | a | 1.76 (1.69) | | | | |
| | | | b | -0.50 (-0.67) | | | | |
| Branches | k c ^a | 194 (1-1,182) | k | 184.94 (23.56) | 0.79 (0.79) | 1.03 (0.85) | 66.00 (5.89) | 0.74 (0.76) |
| | | | a | 3.03 (1.84) | | | | |
| Stem bark | k c ^a h ^b | 21 (1-78) | k | 8.08 (6.85) | 0.83 (0.83) | 0.83 (0.97) | 4.99 (5.05) | 0.82 (0.82) |
| | | | a | 1.55 (1.46) | | | | |
| | | | b | 0.47 (0.54) | | | | |
| Stem wood | k c ^a h ^b | 154 (5-675) | k | 18.85 (19.26) | 0.94 (0.95) | 2.03 (2.19) | 26.27 (26.31) | 0.93 (0.94) |
| | | | a | 1.68 (1.61) | | | | |
| | | | b | 0.95 (0.94) | | | | |
| Total aboveground | wl + wbr + + wb + ww (k c ^a h ^b) | 480 (20-1,899) | k | 280.1 | 0.92 (0.91) | 6.57 (10.45) | 77.27 (74.04) | 0.91 (0.91) |
| | | | a | 2.33 | | | | |
| | | | b | 0.19 | | | | |
| Volume with bark | k h ^a d ^b | 0.66 (0.02-2.73) | k | 0.000094 | | 0.0028 | 0.00865 | 0.93 |
| | | | a | 0.65 | | | | |
| | | | b | 1.97 | | | | |

d: diameter at breast height (cm). c: circumference at breast height ($\pi d/100$) (cm). h: tree height (m). Average (min-max) represents the average, minimum and maximum biomass values in each biomass component used to build the models. For biomass models, the values represent the parameters and several model fitting validation tests after simultaneous fitting (in kg). In bracket the validation tests before simultaneous fitting.

In order to take into account the clustered structure of the data, with correlation among consecutive observations within the same tree, model error was modeled as an autoregressive process. The effect of tree size on the tree average WBD was also assessed with regression analysis.

A total of 70 biomass samples were collected for carbon concentration analysis. The purpose was to collect randomly 10 samples of each biomass components (needles, branches, stem bark, stem wood and roots) from different trees. However the number of samples varied due to several reasons. For roots we only used 6 trees. For needles we add 8 samples from a study carried out in the department on *P. pinea*. For branches we used the 10 samples collected in each of the 3 branch diameter classes described in section 2.3. For stem bark we used 6 samples because 4 out of 10 lead to inconsistent results. The method used was the dry combustion method, according to ISO Standard 10694, using a CNS elemental analyzer. To test whether the average values were significantly different from the commonly used 0.5 carbon fraction, we looked at the confidence interval (with 95% confidence) for each biomass component.

Stand carbon stock comparisons

From a carbon budget management perspective we may question which stands hold de maximum carbon stocks: mature stands with a few trees or young stands with high tree density? In an attempt to answer this question for the *P. pinea* stands in this study, we plotted stand basal area measured (G , m² ha⁻¹) for the 101 stands inventoried, with the total carbon in the trees estimated in each stand divided in 5 stand density classes. The estimates for aboveground biomass in each stand were calculated by applying the biomass equations from Table 3 (to each tree), converted in carbon using the carbon fraction for each component (from Table 5) and expressed by unit area (ha).

Results

Allometric relationships

The total aboveground biomass of sample trees varied between 20 and 1,899 kg, the branch and needle biomass ranging from 1 to 1,182 kg and from 3 to 222 kg,

respectively. The stem wood ranged from 5 to 675 kg and the stem bark from 1 to 78 kg (Table 3). The branches represented the most important fraction of the aboveground tree biomass (average $43\% \pm 2\%$) followed by the stem wood (average $37\% \pm 2\%$), needles (average $13\% \pm 1\%$) and stem bark (average $7\% \pm 0.3\%$). Diameter at 1.3 m (d) and height (h) were the most important independent variables in all equations and accounted for more than 71% of the variability of the different biomass components and volume equations (Table 3).

Overall validation statistics with simultaneous fitting were better for branches but decreased substantially for needles remaining practically the same for stem (wood and bark) components (Table 3). The $M_{\text{efficiency}}$ for total aboveground biomass was the same for both sets (0.91), but for needle biomass equation in an independent model using sapwood area was high, suggesting that this variable provides a good means to predict needle biomass (Fig. 2).

For volume with bark, the values varied between 0.02 to 2.73 m³ with a high $M_{\text{efficiency}}$ (n = 52).

The biomass estimates using Montero *et al.* (2005) equations are well correlated with the observed values (see Fig. 3). When testing the probability of the differences between variances of the two datasets we conclude that there are statistical differences for needles (F-test; $p = 0.01 < 0.05$) but not for stem and branches ($p = 0.20$ and 0.38). However when looking at the absolute errors

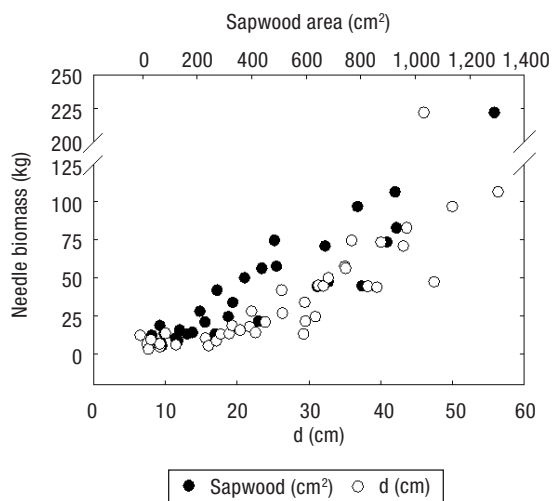


Figure 2. Needle biomass (kg) (y) expressed as a function of (x) that can be either d (cm) or sapwood area (cm²) measured at the base of the live crown. Nonlinear model fitted: $y = k x^a$. For the fitting with: a) $x = d$: $k = 0.06$, $a = 1.87$, $R^2_{\text{adj}} = 0.62$, $E_{\text{efficiency}} = 0.59$, $n = 40$; b) $x = \text{sapwood}$: $k = 0.06$, $a = 1.08$, $R^2_{\text{adj}} = 0.78$, $E_{\text{efficiency}} = 0.70$, $n = 32$.

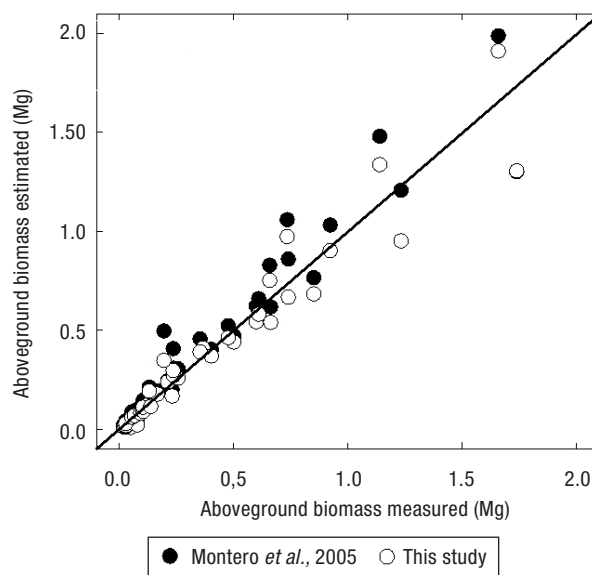


Figure 3. Left graph: correlation between the total aboveground biomass (Mg) measured in the 40 trees harvested and the estimates obtained using Table 3 equations and the biomass equations for *P. pinea* developed by Montero *et al.* (2005) (in Mg).

(difference between the measured and the estimated value) we observed that the estimates are quite biased. The average percentage error computed as the average of the relative error (difference between the measured and the estimated value over the measured value expressed as a percentage) for the 40 trees, resulted in an overestimation for stem and branches (22.2% and 55.3%, respectively) and a underestimation for needles of 23.4% using Montero *et al.* (2005) equations.

Needles/aboveground biomass tends to decrease with stand development (from $21\% \pm 3\%$ at < 20 cm d class to $9\% \pm 3\%$ at $d > 40$ cm) as well as the stem/aboveground biomass with a minimum at $d > 0$ cm with $36\% \pm 5\%$ (Fig. 4c). For the ratio of branches/aboveground biomass there is a tendency to increase as stands gets less denser reaching a maximum at $d > 40$ cm with $55\% \pm 4\%$. For trees less than 20 cm (that is young trees in dense stands), biomass allocation to the crown (and specially branches) seems to be a priority, representing more than 60% of the total aboveground biomass.

The observed decrease in the ratio of productive (needle) to respiring biomass (branches+stem wood + stem bark) as stand gets older (Fig. 4a and 4b) is rather expected (Ryan and Yoder, 1997) and is related with higher construction and maintenance respiration costs with woody tissues. Nevertheless, this decreasing rate is very smooth for d classes higher than 20 cm (average

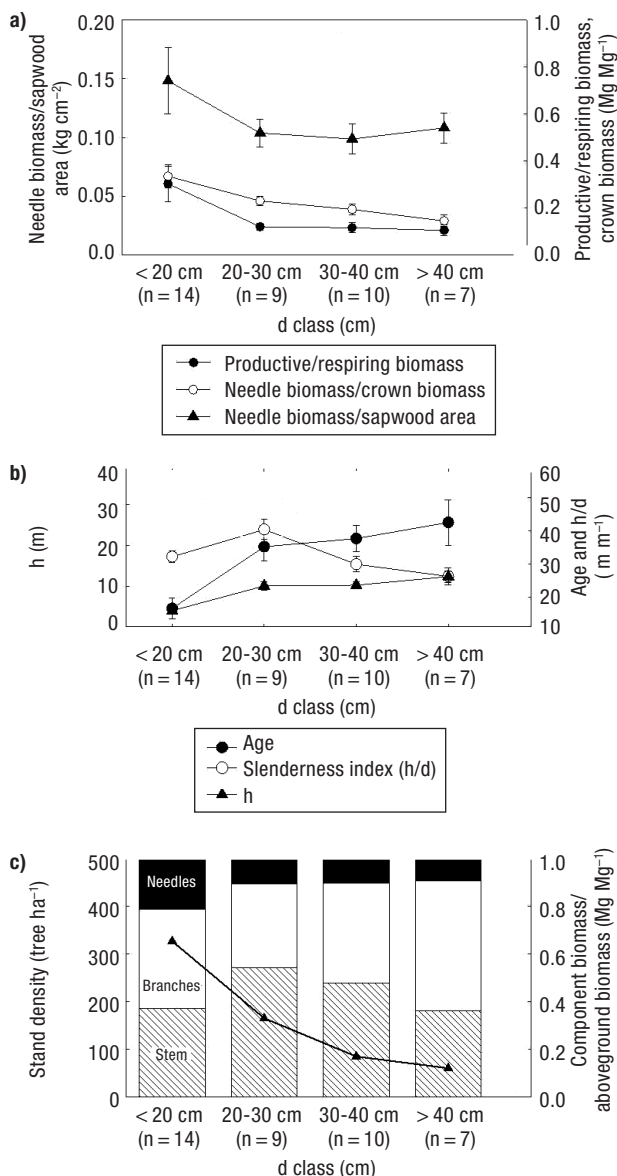


Figure 4. Average values and standard errors calculate for each diameter at breast height class for the following variables: a) Ratio between the productive (needle) to respiring biomass (branches + stem wood + stem bark) (Mg Mg^{-1}); ratio between the needle biomass to crown biomass (Mg Mg^{-1}); ratio between the needle biomass to sapwood area measured at the crown base (kg cm^{-2}). b) h: height (m); age; h/d: height/diameter at 1.3 m (m m^{-1}). c) Stand density (trees ha^{-1}); ratio between each biomass component to total aboveground biomass: Black boxes (needles), white boxes (branches), stripe boxes (stem). n in the axis represent the number of trees used in each class.

$12\% \pm 0.3\%$). The slenderness index was low at $d < 20$ cm because trees at this stand density levels invest little in height compared with diameter (Fig. 4b) and presented a peak at 20-30 cm decreasing thereafter.

Expansion factors and root-to-shoot ratio

Average BEF_i values were higher for branches with $0.57 \pm 0.015 \text{ Mg m}^{-3}$ followed by stem wood ($0.42 \pm 0.002 \text{ Mg m}^{-3}$), needles ($0.12 \pm 0.005 \text{ Mg m}^{-3}$) and stem bark ($0.06 \pm 0.002 \text{ Mg m}^{-3}$) (Table 4). The aggregated $\text{BEF}_{\text{total}}$ was higher for total aboveground ($1.18 \pm 0.01 \text{ Mg m}^{-3}$), followed by the crown ($0.69 \pm 0.014 \text{ Mg m}^{-3}$) and then for stem (wood + bark) ($0.49 \pm 0.003 \text{ Mg m}^{-3}$). The highest variability was found for $\text{BEF}_{\text{branches}}$.

Plotting the aggregated BEF with stand variables (N, G, hdom and Volume), N was the variable that presented the best correlations with BEF_i (Fig. 5) showing a decreasing pattern for aboveground and $\text{BEF}_{\text{crown}}$ and an increase for BEF_{stem} .

Maximum $\text{BEF}_{\text{crown}}$ was 1.08, decreasing to 0.41 in very dense stands with a typical exponential decay curve shape when plotted over stand density (Fig. 5 and Table 4). The opposite is observed for BEF_{stem} with a much smaller variation from 0.41 to 0.57. $\text{BEF}_{\text{aboveground}}$ showed the same tendency than $\text{BEF}_{\text{crown}}$.

Regarding the root system, we observed that roots between 5 and 30 mm represents the higher fraction of the total root biomass (63%), followed by fine (20%) and coarse roots (17%). The root-to-shoot ratio found for the 6 trees harvested was 0.30 ± 0.03 . The horizontal superficial root exploration observed in the surface layer exceeded 1.5 to 2 times the tree crown projection area and about 90% of the total root biomass was in the top 50 cm. Regarding root development in depth, we also observed that fine roots were able to penetrate in severely compacted horizons which can be extremely important for groundwater uptake in the dry season.

Table 4. Biomass expansion factors (BEF_i in Mg m^{-3}) for each tree component (needles, branches, stem bark and stem wood) and aggregated BEF_i (in Mg m^{-3}) (crown, stem and total aboveground). Columns represent the average, minimum, maximum and the standard error (s.e.) for BEF_i for each component. The number of plots used for BEF_i calculations equals 101 (stand characteristics are described in Table 2)

| BEF_i | Average | Min | Max | s.e. |
|--------------------|---------|------|------|-------|
| Needles | 0.12 | 0.06 | 0.28 | 0.005 |
| Branches | 0.57 | 0.28 | 0.99 | 0.015 |
| Stem bark | 0.06 | 0.04 | 0.11 | 0.002 |
| Stem wood | 0.42 | 0.36 | 0.11 | 0.002 |
| Crown | 0.69 | 0.41 | 1.08 | 0.014 |
| Stem (wood + bark) | 0.49 | 0.41 | 0.57 | 0.003 |
| Total aboveground | 1.18 | 0.97 | 1.50 | 0.010 |

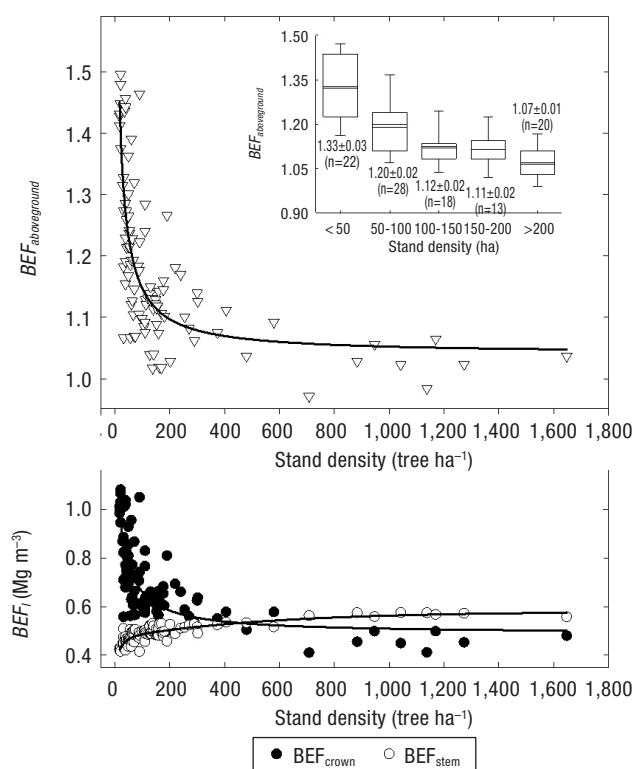


Figure 5. Biomass expansion factors (BEF_i , $Mg\ m^{-3}$) plotted with stand density. Graph in the bottom: BEF_{crown} (branches and needle biomass over volume with bark) and BEF_{stem} (wood and bark biomass over volume with bark). Graph in the top: $BEF_{aboveground}$ (aboveground biomass over volume with bark). Biomass in $Mg\ ha^{-1}$ and volume in $m^3\ ha^{-1}$. Lines represent the trend line ($n = 101$). Right graph: box plot of $BEF_{aboveground}$, by stand density classes. Average and median values represented in the box with a strong and smooth line, respectively. Box boundaries are 25 and 75th percentiles and 90th and 10th percentiles in whiskers. Average values, standard error and the number of plots used in each density class represented in the top of each box.

Conversion factors

Wood basic density

Average WBD for all trees weighted by the disks cross diameter in the stem was $0.51 \pm 0.01\ Mg\ m^{-3}$ (min- $0.43\ Mg\ m^{-3}$ and max- $0.60\ Mg\ m^{-3}$). Figure 6 shows the vertical distribution of WBD in trees with different sizes. Taller trees presented the higher average values ($0.55 \pm 0.01\ Mg\ m^{-3}$) and the shorter trees showed the lowest ($0.47 \pm 0.02\ Mg\ m^{-3}$). We also observed higher values in the base of the stem compared to the top. The regression analysis lead to the following model with the model error modeled as a 2nd order autoregressive process (all parameters significantly different from zero for $p = 0.05$):

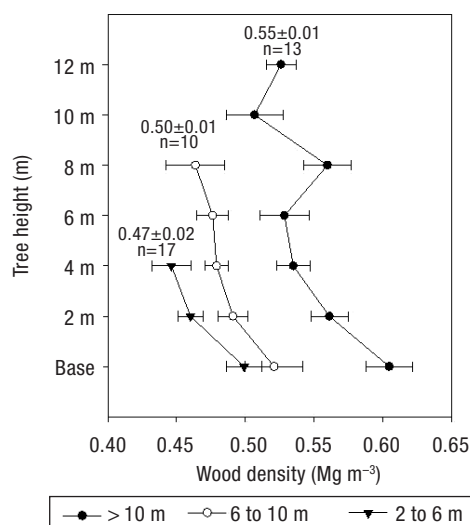


Figure 6. Mean wood basic density ($Mg\ m^{-3}$) in each height classes (2 to 6 m, 6 to 10 m and > 10 m). Standard errors represented in horizontal bars. Values in the top are the average, standard error and number of samples used for calculations in each high class. All pairwise multiple comparison procedures (no statistical differences for 2 to 6m and 6-10 m class, $p = 0.226$, Tukey test).

$$WBD = 443.63 + 10.17\ h - 20.78\ h_i + 20\ h\ h_i$$

$$(R^2 = 0.46),$$

where WBD is wood basic density ($Mg\ m^{-3}$), h is tree total height (m) and h_i is height level within the tree (m). Tree diameter at breast height, alone or combined with tree height, did not improve the model for WBD. The following model was found for tree average WBD:

$$WBD = 437.51 + 8.03\ h$$

$$(R^2 = 0.50),$$

where the symbols are as before. These analyses clearly show that WBD depends on tree height, increasing with tree size. Within the tree, WBD decreases from the soil level to the tip.

Carbon fraction in biomass

Average carbon fraction in the dry biomass for branches and roots is not significantly different from 0.5 carbon fraction (Table 5), but they are for stem wood, stem bark and needles taking into account a 95% confidence interval.

Stand carbon stock comparisons

Taking into account the above methodologies, we observe in Figure 7 that the maximum carbon stock in the aboveground biomass is reached in open stands,

Table 5. Carbon fraction in biomass components (Mg of carbon per Mg of dry matter). Columns represent the average, minimum, maximum, the standard error and the number of samples used for each component. Conf. int. (95%) represents the 95% confidence interval for the population mean

| Carbon fraction | Average | Min | Max | s.e. | n | Conf. int. (95%) |
|-----------------|---------|------|------|-------|----|------------------|
| Needles | 0.45 | 0.42 | 0.46 | 0.003 | 18 | 0.44-0.45 |
| Branches | 0.51 | 0.49 | 0.55 | 0.002 | 30 | 0.50-0.51 |
| Stem bark | 0.54 | 0.53 | 0.56 | 0.005 | 6 | 0.53-0.55 |
| Stem wood | 0.53 | 0.50 | 0.59 | 0.008 | 10 | 0.51-0.55 |
| Roots | 0.50 | 0.50 | 0.51 | 0.002 | 6 | 0.50-0.51 |

which correspond to trees in the mature and reproductive stage. Stand carbon stocks are successively higher in stands with less trees compared with dense (and younger) stands for the same G. This will allow to identify, from a carbon budget perspective, which is the more compensatory strategy: protect mature or old stands with large biomass stocks from harvesting and degradation, or to plant new trees that will take a couple of decades to get big enough to have the same amount of carbon as the mature ones. The aboveground estimates are within the range of values reported in the literature for other pines. For example, Janssens *et al.* (1999) found an average of 103 tC ha⁻¹ in a 69-year-old *Pinus sylvestris* in a Belgian Campine region with 556 tree ha⁻¹. Grunzweig *et al.* (2007) refers an average value of 177 tC ha⁻¹ in a 35 year-old with 300 trees ha⁻¹ in Negev Desert, Israel. Evrendilek *et al.* (2006) studied several conifers in Turkey and reported an average

of 137 tC ha⁻¹ in a *Pinus nigra* of 92 year-old forest with 300 trees ha⁻¹. King *et al.* (2007) reported an average of 115 tC ha⁻¹ in a 55 year-old *Pinus resinosa* with 622 trees ha⁻¹ forest in the Upper Peninsula of Michigan.

Discussion

Biomass equations

The tree variables d and h had a significant effect on the allometric relationships for biomass and volume, in agreement with other authors (António *et al.*, 2007; Calama and Montero, 2006). Some studies had tested other variables with success, namely with tree age for eucalypts in Congo (Saint-Andre *et al.*, 2005), stand age for *Pinus pinaster* in Aquitaine (Porté *et al.*, 2002), sapwood area to stem diameter for several boreal species (Bond-Lamberty *et al.*, 2002). The inclusion of the slenderness index (ratio h/d) as a predictor in the needles biomass for *P. pinea* model is possibly related with the response of needle biomass, more than other tree components, to competition since the h/d index is usually associated with tree social status in the stand (Ilomaki *et al.*, 2003).

Simplified biomass models dependent on commonly measured variables like d and h, are advantageous from the application point of view, either for field inventories or data processing. In this study we fitted the equations for the tree component simultaneously with the total biomass expressed as the sum of the components. This was made in order to take into account the correlation between the errors of the several models and also to guarantee that the total biomass estimation (by summing the estimates for each independent biomass component equation), is equal to the total aboveground estimated by the aboveground biomass equation. This restriction has not been taken into account by several authors (*e.g.* Saint-Andre *et al.*, 2005) with the consequent inconsistency in total biomass estimates.

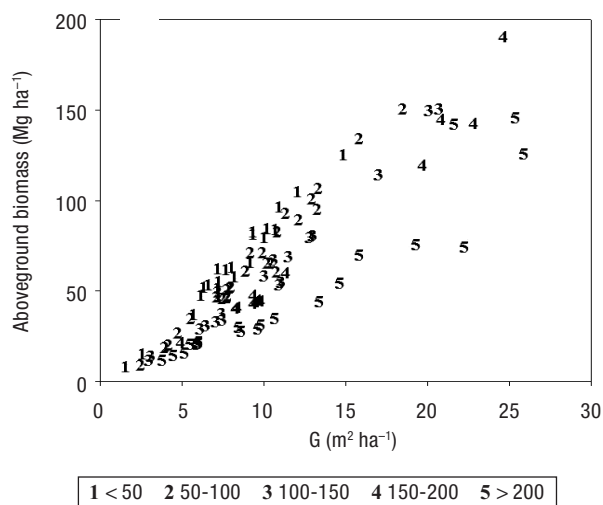


Figure 7. Total aboveground biomass in *P. pinea* stands (Mg C ha⁻¹) plotted with stand basal area (G, m² ha⁻¹) in 5 stand density classes: (1) < 50 tree ha⁻¹, (2) 50-100 tree ha⁻¹, (3) 100-150 tree ha⁻¹, (4) 150-200 tree ha⁻¹, (5) > 200 tree ha⁻¹ in the 101 inventoried (Table 2).

Comparison with independent biomass equations

The differences found between the biomass measured and estimated by Montero *et al.* (2005) may be explained by the fact that these equations only use d as an explanatory variable. On the other hand, the fact that trees from Montero *et al.* (2005) study come from a more continental climate may cause the proportional lower needle biomass (Fig. 1). Concomitantly Montero *et al.* (2005) found, on average, a higher proportion of branch biomass in relation to the aboveground tree biomass (51% compared with 43% in this study) which can be explained by stand management. However no information is available regarding this issue. These differences in biomass estimates highlights the importance of validating equations and factors outside the range of ecological region from where they are going to be applied. However, the number of trees sampled and the small geographical area from which the trees were harvested in this study is clearly very limited for making any generalizations in the statistical sense. Nonetheless, the results provided here can be useful as a general indicator of overall relationships in *P. pinea* in the most important Portuguese productive area.

The equation for needles after simultaneous fitting was notably worse than the independent model (Table 3). Since the average needle biomass in total aboveground biomass is not neglectful (around 10%), the set of biomass equations after simultaneous fitting should be used when all the components have to be quantified together. However, for isolated estimates of this component (for example leaf area calculations), the independent needle equation from Table 3 should be used. Alternatively, we propose 2 independent equations (Fig. 2) based on d and sapwood in a power function that can come as alternatives for use in some carbon balance models, since the independent variables are closely linked with physiological processes underlying these models.

Stand development and biomass partitioning

Needles

From Figure 4c we conclude that younger *P. pinea* trees ($d < 20$ cm) allocate considerably more resources to the production of photosynthetic tissue ($21\% \pm 0.03\%$) compared to the remaining aboveground tree compo-

nent. The higher investment in the needle biomass is a common survival strategy in the juvenile phases but the proportion in relation to aboveground tree biomass decreases as stands get older due to the formation of new wood structures and the maintenance of the older ones (Ryan and Yoder, 1997). The decrease in the proportion of productive (needles biomass) to respiring biomass (stem wood, stem bark and branches) reflects this trend (Fig. 4a): the decrease is abrupt in the first stages (from $30\% \pm 8\%$ in < 20 cm d class to $12\% \pm 2\%$ in 20-30 d class) but then slows down beyond this class. This is consistent with the observations for the ratio needle biomass to sapwood area: a significant decrease in the ratio of needle biomass to sapwood area from $d < 20$ cm to 20-30 cm class (0.15 ± 0.03 kg cm^{-2} to 0.10 ± 0.002 kg cm^{-2}) and then maintenance above 30 cm d class in around 0.10 kg cm^{-2} . This means that trees continue to produce leaves as a response to light availability with no limitations in water supply to the crown, since the sapwood area increases concomitantly (McDowell *et al.*, 2002; Mencuccini and Grace, 1995).

Stem

The lower h/d index found at $d < 20$ cm at high densities (average 326 tree ha^{-1}) is not expected, mainly because the h/d in the following d class is higher (Fig. 4b). Although some authors refer that trees in competition tend to invest more in height growth instead of diameter growth (Ilomaki *et al.*, 2003), this does not seem the case in this study. It is possible that for these small trees, stand density is not enough to stimulate height growth as seem to be the case in the above mentioned study (tree density ranged from 400 to 5,000 tree ha^{-1} , respectively). On the other hand, the proportionally high needle biomass found at these stages, consistent with *P. pinea* light demanding characteristic, suggest a higher tree investment in a more efficient water conducting system and therefore in d (and sapwood) growth. The decrease in the slenderness index after 20-30 cm d class is a result of the light exposure due to the stand density decline, suggesting the higher investment in diameter growth with a concomitant stabilization of height growth at 11 m above 20-30 cm d class (Fig. 4b). This is advantageous from the hydraulic point of view since the hydraulic resistance increases as trees get older and taller, resulting in limits to carbon assimilation (Ryan and Yoder, 1997). On the contrary, *P. pinea* trees seem to be investing in main-

taining the balance between needle biomass to sapwood area (Fig. 4a) probably as a strategy to protect the xylem water conducting system. This is rather important at the peak of reproductive phase, when all the resources are being allocated to fruit production (around 30 years old). Many authors working with other species (McDowell *et al.*, 2002; Mencuccini and Grace, 1995; Waring *et al.*, 1982) refer that the ratio of needle area/sapwood area must decrease with increasing h and age, in order to reduce hydraulic resistance. This is especially important in dry climates where vapor pressure deficits are higher. This has been reported in several species from temperate to dry climates (DeLucia *et al.*, 2000), but have never been studied for *P. pinea*. In this study, this was evident in the first stages of the life of the tree (from d class < 20 cm to 20-30 cm) but stopped thereafter, even with an increase in age and the (smooth) increase in h . Above 20-30 cm d class, no structural adjustments were recorded regarding needle biomass/sapwood area. This could either be explained by the low intra-specific competition mentioned above or to the ability of the root system to support foliage with water, which seems to be efficient in *P. pinea*, in open stands (see results for roots in section 3.2). This fact was also observed for Holm oak in South Portugal (David *et al.*, 2007).

Branches

It is noteworthy that the proportion of branches gradually increases as stand density declines reaching more than 40% of the aboveground biomass (Fig. 4c). This has probably to do with a *P. pinea* strategy to enhance seed production at reproductive stages (Mutke *et al.*, 2005b). Note that if there were any hydraulic limitations, the first structures to be damaged would be the tip of the branches where the hydraulic resistance is higher (Mutke *et al.*, 2003). However at these stages, the absence (or reduced) competition for light, and probably the efficient access to water, allow co-dominant branches to stiffen due to secondary growth and to be maintained in the canopy surface in the best light conditions, suffering less down-bending. These heavier and stronger branches are the ones able to sustain more and heavier cones (Mutke *et al.*, 2005c). This explains why higher cone productions can only be achieved in open stands (usually with less than 100 trees ha^{-1}).

This higher allocation pattern to branches in the mature stands may also explain why older stands with

less trees are able to retain more carbon than denser stands with the same G (Fig. 7). This will allow to identify, from a carbon budget perspective, which is the more compensatory strategy: protect mature or old stands with large biomass stocks from harvesting and degradation, or to plant new trees that will take a couple of decades to get big enough to have the same amount of carbon as the mature ones. Concomitantly, Mutke *et al.* (2005b) emphasizes that the biomass allocation to cone production is similar to stem volume growth which may exacerbate the importance of open and mature stands to overall carbon stock and sequestration.

Expansion factors and root-to-shoot ratio

Average BEF_i values found in this study (Table 4) are amongst the highest reported for Mediterranean and Northern European species and much higher than other pines (Gracia and Sabaté, 2002; Lehtonen *et al.*, 2004; Levy *et al.*, 2004; Peichl and Arain, 2007). The higher $BEF_{aboveground}$ found is in consistence with the species structure and geometry – lack of apical dominance with a polyarchic ramification resulting in a crown shape wider than deeper (Mutke *et al.*, 2005c) and with a proportionally heavier crown compared with the rest of the aboveground woody tissues. Biomass allocation pattern for *P. pinea* changes significantly with stand density (Fig. 5) so stand density is, to a certain extent, a surrogate for stand development, with older stands having the lower densities. This conclusion shows that the use of a single average value for the species or species group for biomass calculations at stand level in *P. pinea* can lead to highly biased estimates. This has been well demonstrated by several studies on other species (Lehtonen *et al.*, 2004; Tobin and Nieuwenhuis, 2007).

Regarding the root-to-shoot ratio, there is still a huge lack of publications on consistent and comparable methods of root measurements in adult trees and very few on *P. pinea*. The error associated with fine roots biomass sampling was considered to be very small using this methodology because all the soil volume explored by the roots was taken into account including root development in depth till the sandstone rock (Carlos Pacheco, personal communication). Janssens *et al.* (1999) for example also states that roots with less than 1 mm represents less than of the total tree biomass. Fernández (2004) reported a root-to-shoot ratio of 0.19 for *P. pinea* in Andalusia, 0.24 for *Pinus stobus* in Canada (Peichl and Arain, 2007) and 0.26 in the review

of Cairns *et al.* (1997). Levy *et al.* (2004) reported an average root-to-shoot ratio of 0.36 for conifers in Great Britain. IPCC (2003) suggest as default root-to-shoot for conifer forest plantations of 0.32 ± 0.08 . A study carried out with *Pinus pinaster* in center Portugal in a Regosol using the same methodology as this study, reported a root-to-shoot of 0.28 ± 0.05 ($n=5$) (Sónia Faias, personal communication). The 0.3 factor for root-to-shoot found here, although not statistically representative should be used as an alternative to the ratios found in literature. But this is a subject that clearly needs more investigation.

Conversion factors

Wood basic density

Average stem WBD found in this study was 0.51 ± 0.01 Mg dm m^{-3} . Other values in the literature for the same species reports 0.52 ± 0.08 Mg dm m^{-3} for the stem (Gracia and Sabaté, 2002), Oliveras (2003) reported 0.38 ± 0.02 Mg dm m^{-3} for roots and 0.55 ± 0.03 Mg dm m^{-3} for branches. Montero *et al.* (2005) cite the value 0.50 for *P. pinea* although do not mention to which component refers to. Carvalho (1996) reported 0.55 Mg dm $_{12\% \text{ humidity}} m^{-3}$. The average values reported in this study are therefore very close to the ones referred by other authors for the same species. However there are intra-specific discrepancies that should be taken into account when dealing with very old or very young even-aged stand carbon calculations, justifying in some cases the use of dimension-dependent WBD values. Higher WBD is generally found in taller trees compared with smaller ones which may be related with tree age. The analysis from tree-rings in this study shows that taller trees are also the oldest. This has to do also with a decrease in the juvenile wood and an increase of the heartwood percentage (which has higher WBD) which is frequently accompanied by resin and other extractives. Resinous deposits may be inflating overall WBD in older trees and may also explain the elevated WBD in the base disks since the wounds for resin extraction were performed around breast height. The discrepancy found for WBD inside the crown of the taller trees may be explained by the proximity to foliage, where physical and chemical properties of the juvenile wood are more variable. These results are in consistency with the results reported in Zobel and Buijtenen (1989).

Carbon concentration in biomass

Recent publications strongly discourage the use of the common 0.5 carbon fraction of biomass (Mg of carbon per Mg of dry matter). Bert and Danjon (2006), studying *Pinus pinaster* stands in France, found statistical differences from the 0.5 value for all the tree components carbon concentration, always higher than 0.5. Lamlo and Savidge (2003) found a higher carbon concentration in early wood compared with late wood in conifers, and also argue that the method and sample preparation influence the final carbon concentration results. However, other authors such as Ritson and Sochacki (2003) did not find any statistical difference between carbon concentration in aboveground components in *Pinus pinaster* in Australia and the 0.5 factor. Although we had found a statistical difference between the carbon concentration and the 0.5 factor for some components, we believe that the arguments presented above and the fact that elemental composition of completely dry wood is remarkably uniform (molecular formula $CH_{1.44}O_{0.66}$), the 0.5 factor overcomes the other potential sources of error related with species, stands or the method used in the carbon elemental analysis.

Conclusion

In this study we present and emphasize the importance of species-specific methods for stand level carbon estimates in *P. pinea* stands. We found that biomass allometry varies considerably with stand management, meaning that generic and averaged expansion and carbon factors used to convert volume in biomass can produce misleading carbon estimates. Biomass equations should be species and geographically specific or at least validated and adjusted if necessary to the study area. *P. pinea* stands are important carbon stocks, especially mature stands in the reproductive stages. Maximum carbon accumulated in the trees in mature stands with very low tree densities is comparable to carbon stocks in denser stands from other pines reported in the international literature. This results from the high *P. pinea* investment in crown biomass, especially branches, in order to support a high cone production. Future studies should address the role of *P. pinea* stands as carbon sinks and clearly more investigation should be done over the importance of soil, cones and root systems in overall *P. pinea* carbon balance.

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