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Research paper

Improving biomass estimation for *Eucalyptus globulus* Labill at stand level in Portugal

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ABSTRACT

Two systems of equations for predicting stand level aboveground biomass and biomass per tree component (wood, bark, branches and leaves) were developed taking into consideration the specific characteristics of the stands. The two systems differ by considering or not stand age as one of the regressors. Data from permanent plot, trials and continuous forestry inventory was used. It included data from first rotation and coppiced stands that represent the existing range of ages, stand densities, sites and management options in Portugal.

The models have a good predictive capacity (adjusted $R^2 > 0.97$) using only stand variables easily accessible in forest inventories; stand age, stand density, dominant height, basal area and cultural regime.

The proposed equations where used on National Forestry Inventory plot data and the results obtained where compared to the inventory results and estimates obtained using tree level allometric equations and Biomass Expansion Factors (BEF's). The comparison of the four approaches showed that the use of stand level methods gives as accurate results as the use of tree level methods. The use of BEF's resulted in the least accurate method for estimating biomass, with an average mean error of 17%. In contrast, the proposed equations estimate biomass values with a mean error of 9% and are the best option for biomass estimates in short rotation forestry, where the objective is to obtain biomass estimates for short rotation stands (2–5 years). They also allow tree component biomass estimates, something that is not possible using the existing BEF's for *Eucalyptus globulus*.

1. Introduction

The use of biomass as renewable energy has become a common topic. Short-rotation tree coppices of the genera Eucalyptus, Salix, Populus, Castanea, Alnus and Betula have become increasingly common in the EU [1,2]. These coppice crops have seen their importance rise, because biomass is seen by many European governments as having an important role in meeting commitments under the Kyoto Protocol [3]. The Portuguese forest, as far as the Kyoto Protocol is concerned, has been a carbon sink since 2003. Considering an average price of 5.94 € for each tonne of carbon dioxide equivalent, the Portuguese forest is worth 89.3 M € [4].

The results of the 6th National Forest Inventory (NFI) show that, in 2010, the Portuguese forests represented 35% of the territory. The main forest species that represent about 72% of the national forest area are, in decreasing order, blue gum (25.8%), cork oak (23.4%) and maritime pine (22.7%). The blue gum area had an increase of 13.2% (about 95 000 ha) between 1995 and 2010 [5]. As the species with the biggest representation, blue gum (*Eucalyptus globulus*) biomass estimates are of great importance for the assessment of carbon sequestration by the Portuguese forests and for the quantification of biomass for energy.

Direct biomass measurements is only viable at a small scale and even in this case it always implies the sampling of a small number of trees. Stand biomass is therefore usually estimated using remote sensing techniques or through equations that use other measured variables as predictors.

Remote sensing techniques have been drawing attention due to time and cost reduction when compared with specific data gathering in the field [6]. They can be used to collect stand level data and make the process even easier and faster. For example, LiDAR provides accurate measures of woody volume [7] and it can also be used to directly quantify some characteristic's such as tree height

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and canopy height that can be used to improve biomass estimations. These techniques have been having success, but as the forest structure gets more and more complex, the estimates start to lack reliability and more information at stand level is needed, not only to increase estimates reliability [6], but for calibration and validation [8]. Biomass estimates from remote sensing still currently rely on field based training datasets [7], but the improvement depends also of efficient image processing techniques [9,10]. There is also the problem of the number of environmental and topographic factors that can affect the accuracy of the estimations [10] and the fact that the images become saturated at fairly low biomass levels [11].

Remote sensing biomass estimation is still a challenge, investigation is still needed to understand and identify the flaws in this process and reduce the estimates uncertainty [12]. Field data is therefore still considered the most precise option for aboveground biomass estimations [6]. The combination of forest inventory data with estimation models is the most used method to estimate stand biomass.

Stand level biomass estimations may be obtained by biomass prediction models (e.g. Refs. [13–17]) or through the so-called Biomass Expansion Factors (BEF's) that directly convert volume into biomass (e.g. Refs. [8,13,18]). One problem with this methodology is the fact that they are based on a volume estimation which has also associated some error. BEF's vary between species, age, place, stand characteristics and also volume but it is very common to assume a species-specific value. Some authors (e.g. Refs. [19–21]) developed equations to predict the BEF value taking into account other stand variables. González-García et al. [14] compared three approaches – biomass equations, BEF equations and constant BEF's – to predict aboveground biomass at stand level in *E. nitens* and concluded that biomass equations provided the most accurate predictions for the stem component and for aboveground biomass.

The main objective of this study was to improve stand level aboveground biomass estimation for blue gum stands by developing a system of compatible equations to estimate total aboveground biomass expressed in terms of dry weight. The developed equations were applied to NFI measured plots and the estimated values were compared with tree and other stand level estimates to access the impact of using these methods for biomass estimation.

The first task was to develop simple systems of equations to predict total and per tree component aboveground biomass from easily obtained stand variables. The use of allometric equations to estimate above-ground biomass in Australia [22] showed evidence that application of ‘stand-scale’ equations is likely to be as effective as the use of more site- and species-specific equations applied to individual trees in a stand. For example, stand-based equations that enable biomass to be predicted from basal area, mean height, stand density, or combinations of these variables, appear to be reasonably robust [22].

According to Clutter et al. [23], explicit functions can be used to predict actual production in terms of biomass and volume using stand height, a stand density indicator, basal area, age and site index. Following this principle, Barrio-Anta et al. [24] considered reasonable to relate stand production with the product of biomass or volume of the representative tree – given by quadratic mean diameter and dominant height – and the number of trees per hectare and estimate stand biomass or volume in this way. This is very similar to the medium tree technique developed in the 60's and 70's by several investigators [25–28].

The growth and yield model Globulus [16,17] includes a system of allometric equations for total and per tree components biomass estimation at stand level. The equations are site-specific by expressing biomass as a function of dominant height and basal area and using site index, stand density and age to localize the parameters.

Site index (S) is an indirect measure of the potential growth at a site that assumes that the dominant height growth of a stand is independent of changes in the environment and that it is not influenced by stand density. When growth conditions are stable, one can use this concept without problems, but when the conditions are variable, the growth response is highly non-linear and the relationships can be very difficult to predict. It is known, for example, that the relationship between tree height and diameter varies with altitude in such a way that blue gum trees that are grown in higher altitudes tend to be shorter and thicker [29], resulting in different productivities for the same value of S. Considering this variability issues and also the fact that S is dependent on the equation used to estimate it, it was decided that the inclusion of S as a variable to localize the a, b and c parameters must require a reasonable improvement in the predictive ability of the models, otherwise this variable should not be included.

Besides providing an easier to apply method for biomass estimation that relies only on stand level variables that can easily be obtained by simple forest inventory or using remote sensing techniques, the system must provide a consistent basis for evaluating forest biomass across regional boundaries as well as to provide compatible predictions of stand level aboveground biomass and of the largest aboveground biomass components of the tree: stem wood, stem bark, branches and leaves.

This study also seeks to give answers to some questions that appeared while preparing this paper:

1. Can stand level equations give biomass estimates nearly as accurate as the ones obtained when using tree level measurements?
2. What is the best method for biomass estimation in short rotation forestry?
3. How large is the error of using stand level and not tree level equations in terms of amount of biomass estimated?
4. Is there a significant improvement in the predictive ability of the models when the allometric constants are expressed as a function of stand and site variables, such as age, dominant height, stand density or site index?
5. Is there a need to use different parameter estimates for planted and coppice regenerated stands?

2. Material and methods

2.1. Data

2.1.1. Model development

The data used in this work came from the available database for blue gum plantations in Portugal that includes data from permanent plots, continuous forest inventory and spacing and fertilization trials. The plots are located throughout the species area of distribution in Portugal and represent the existing range of ages, stand densities, sites and management options. The existing data from some permanent plots and trials also gives information for less usual management options, such as higher densities and older trees. Plot size ranged from 100 to 2464 m^2, depending on data source. Continuous forest inventory plot size is usually 400–500 m^2, but in permanent plots and trials, plot size varies. Diameter at breast height was measured in every tree and total tree height in dominant, model trees or all the trees, depending on data provenience. Non-measured tree heights were estimated with the height-diameter curve from Tomé et al. [30]. Aboveground biomass and biomass per tree component (stem wood, stem bark, branches