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Cumulative continuous predictions for bole and aboveground woody biomass in *Eucalyptus globulus* plantations in northwestern Spain

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ABSTRACT

At present there is increasing interest in modelling biomass to estimate carbon sequestration or the availability of forest products for use as bioenergy. The biomass of different tree components can be estimated to provide more detailed information. However, the different components have not been clearly defined. Moreover, the greater the number of components considered, the more difficult it is to fit the system of equations with any guarantee of statistical robustness. To overcome these limitations, we developed a continuous function that predicts cumulative biomass from the stump until any top diameter (including the biomass of branches). We also used two different methods to predict bole biomass: a cumulative continuous biomass function and conversion from volume to biomass by use of a taper equation and average wood density. We used a mixed-effects modelling framework to account for correlated errors in developing the taper equation. We developed a separate equation to estimate the foliar biomass for use in estimating total aboveground tree biomass. The cumulative aboveground woody biomass equation is implicitly additive, and no heteroscedasticity was observed, thereby resolving two of the main modelling goals in the development of biomass equations. For predicting cumulative bole biomass, estimation from volume generated less error, after bias correction, than direct estimation. Moreover, the indirect method also yields useful variables such as volume and height limits. Other variables such as carbon and nutrient contents, calorific power, ash content, etc. can be estimated by multiplying the mean contents by the predicted biomass or, for more accurate predictions, by using equations based on the relative diameter.

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1. Introduction

Interest in obtaining accurate biomass predictions has increased in recent years because of the importance of these in quantifying carbon sequestration and determining the availability of forest products for use as bioenergy. Both elements are also directly related to climate change, as good forest management can help reduce carbon emissions [1]. Atlantic and central European countries have the largest carbon sequestration potential in Europe [2]. Therefore, forest managers in these areas require tools that enable prediction of total tree biomass, although more detailed estimates are sometimes necessary.

Estimation of total and component tree biomass is mainly obtained by fitting models that relate these variables to easy-to-measure tree variables. Diameter at breast height and tree height are the most commonly used variables for this purpose [3]. Zianis et al. [4] reported 607 biomass equations for Europe, which are completed by 188 equations reported by Muukkonen and Mäkipää [5]. Most of these equations are based on the allometric model ($y = k\,x^a$), where k and a are parameters, x is a variable defining tree dimension, and y is the estimated biomass. Although total tree biomass is often estimated, separation of tree biomass into different components is required for other objectives [6], making it necessary to develop a different equation for each biomass component considered. One problem found when modelling aboveground biomass is that the woody components are defined by diameter limits, which vary between studies, making it difficult to compare predictions for different species or regions. In addition, as the number of components considered increases, the system of equations becomes more complex and more difficult to fit with any guarantee of statistical robustness.

For continuous prediction of bole biomass up to any diameter limit, early studies used ratio equations ($\widehat{R}$) to relate estimated total bole biomass ($\widehat{A}_b$) to merchantable biomass ($\widehat{w}_{ab} = \widehat{R}\ \widehat{A}_b$, [7]). Another way of estimating bole biomass is to multiply volume (m^3) by wood density (δ, kg m^{-3}). Several studies have examined the variation in wood density and concluded that within tree variation is often greater than between tree variation [8]. Specifically, the relation between δ and relative tree height has been demonstrated [9,10]. However, this relation is difficult to explain, as δ can either increase or decrease with tree height [11]. Parresol and Thomas [12,13] introduced the "density-integral" method for the direct development of an individual-tree bole biomass equation based on a taper equation and the variation in δ at the individual-tree level. The advantage of this method is that it is possible to predict bole volume and biomass at a specified diameter or height limit. Nevertheless, this method cannot be used to yield total aboveground woody tree biomass (bole + branches).

The overall objective of the present study was to develop equations for predicting total and disaggregated aboveground tree biomass for Tasmanian blue gum (*Eucalyptus globulus* Labill.) in Galicia (north-western Spain). Tasmanian blue gum is one of the most important species in the region in terms of area covered and production. The species was introduced in Galicia in the second part of the 19th century and currently covers around 4000 km^2 in pure and mixed stands [14]. Nearly 4 million cubic meters of *Eucalyptus* spp. were harvested in Galicia in 2012 [15], making it the main species in terms of harvested volume in the region. In Galicia, the timber from this species is mainly used to produce pulpwood and chipboard, which are usually obtained from harvested trees with top diameters of 10 and 5 cm, respectively [15].

In order to address the overall objective of the study, the following specific objectives were identified: (i) development of a continuous woody tree biomass equation (w_a, bole and branches) that predicts cumulated biomass from stump until any top diameter (d); (ii) continuous prediction of cumulative bole tree biomass (w_{ab}) by using two different approaches: directly by using an equation and indirectly by conversion of volume to cumulated biomass; and (iii) development of an equation for estimating foliar biomass. For a better understanding of these variables, w_{ab} and w_a, which are both related to top diameter, are represented in Fig. 1. The nomenclature used in this study is summarised in Table 1.

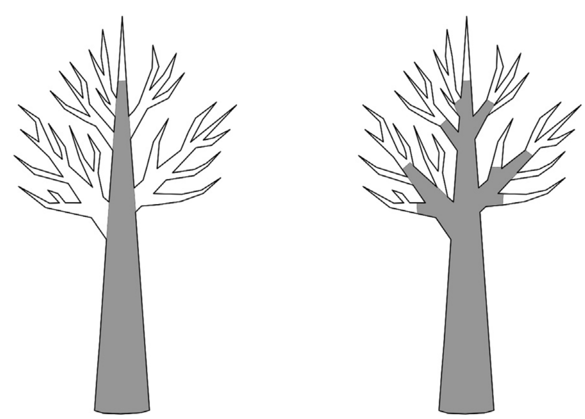

Fig. 1 – Representation of w_{ab} (left) and w_a (right) in relation to the same top diameter (d).

Table 1 – Nomenclature used in the study.

Tree variables	D	Diameter (cm) at breast height (1.3 m above ground level) over bark
	H	Total height (m)
	d	Top diameter (cm)
	A	Total aboveground woody biomass (kg, included bole and branches)
	A_b	Total bole biomass (kg)
	A_l	Total foliar biomass (kg)
	w_{ab}	Cumulative bole biomass (kg)
	w_a	Cumulative aboveground woody biomass (kg)
Stand variables	t	Stand age (years)
	H_0	Dominant height (m), defined as the mean height of the 100 largest diameter trees per hectare
	N	Number of trees per hectare
	G	Stand basal area (m^2 ha^{-1})