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Generalized biomass equations for Stone pine (*Pinus pinea* L.) across the Mediterranean basin

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ABSTRACT

Accurate estimates of tree biomass are strongly required for forest carbon budget estimates and to understand ecosystem dynamics for a sustainable management. Existing biomass equations for Mediterranean species are scarce, stand- and site-specific and therefore are not suitable for large scale application.

In this study, biomass allometric equations were developed for stone pine (*Pinus pinea* L.), a Mediterranean tree species with relevant ecologic and economic interest. A dataset of 283 harvested trees was compiled with above- and belowground biomass from 16 sites in three countries (Italy, Spain, Portugal) representative of the species' geographical Mediterranean distribution. A preliminary approach comparing the ordinary least squares method and the mixed model approach was performed in order to evaluate the most appropriate method for nested data in the absence of calibration data. To quantify the sources of error associated with applying biomass equations beyond the geographical range of the data used to develop them, a residual analysis was conducted.

The allometric analysis showed low intra-specific variability in aboveground biomass relationships, which was relatively insensitive to the stand and site conditions. Significant differences were found for the crown components (needles and branches), which may be attributed to local geographical adaptation, site conditions and stand management. The root biomass was highly correlated with diameter at breast height irrespective of the geographical origin. Biased estimates were found when using site-specific equations outside the geographical range from where they were developed.

The new biomass equations improved the accuracy of biomass estimates, particularly for the aboveground components of higher dimension trees and for the root component, being highly suitable for use in regional and national biomass forest calculations. It is, up to the present, the most complete database of harvested stone pine trees worldwide.

1. Introduction

The Global Forest Resources Assessment (FAO, 2016) estimates that the forests and other wooded lands store globally about 369 billion tonnes (Gt) of CO_2 per year. Over the past 25 years, the global carbon stocks have decreased by almost 11 Gt as a consequence of forests conversion to other land uses and, on a lesser extent, to forest degradation (FAO, 2016).

National forest inventories are the worldwide primary source of information about carbon stocks and carbon sequestration, being therefore an essential tool for defining international agreements regarding the mitigation and adaptation process to climate change. Forest inventory estimates usually rely on species-specific biomass equations and/or biomass expansion factors developed from empirical data. Forest life cycle assessments and carbon footprints accounting are other applications that heavily rely on biomass equation and expansion factors (Demertzi et al., 2016). Therefore, it is of upmost importance to improve the quality of biomass and carbon estimates in order to verify its applicability on large spatial scales (Temesgen et al., 2015).

The development of biomass equations requires harvesting a sample

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of trees, measure them and determine the dry weight of each biomass component. The tree biomass is frequently separated in stem, branches, leaves and roots. Some authors report the branches component by diameter classes as in Porté et al. (2002) or the stem divided in wood, bark and stump (Barreiro et al., 2017). The detail used in biomass separation by components depends on the purpose and mostly on the human and financial resources available. For example, there are substantially less belowground biomass equations because measuring root biomass is more costly and time-consuming than measuring aboveground biomass (Cairns et al., 1997).

Due to tree morphological variability, the allometry between tree biomass and its dimensions tend to be species-specific (Nelson et al., 1999; Teobaldelli et al., 2009). Local environmental conditions (Hulshof et al., 2015), stand management (Cutini et al., 2013) and growing conditions (Naidu et al., 1998; Forrester et al., 2017) also influence biomass growth and their scale ratios. Thus, according to IPCC (2003), it is a good practice to develop species-specific biomass equations with local trees (Temesgen et al., 2015).

Some studies provide biomass equations dependent on stand characteristics (António et al., 2007; Oliveira and Tomé, 2017). However, according to Sileshi (2014), models with multiple predictors may have constrains, such as collinearity or cross-validation problems, and frequently are difficult to interpret from a biological point of view, as compared to simpler models. Typical biomass equations are described by power-law functions that frequently use the diameter at breast height and tree total height as predictors. Sileshi (2014) notice that linear models are also common in the literature although this formulation lacks a biological meaning. This author points that an arbitrary analytical method selection, an inadequate model analysis obtaining ambiguous results are amongst the most frequent mistakes on biomass equations formulation.

Despite the variety of proposed approaches, the end-user very often prefers to adopt existing biomass equations from literature rather than harvesting trees to develop new biomass equations. However, as published biomass equations are usually based on a small number of harvested trees covering a limited diameter classes range (Clark and Clark, 2000), there is a potential problem of applying these equations beyond the allometry range for which they have been developed. Chave et al. (2004) recommend to avoid the development of models from a small sample, indicating a minimum number of 100 harvested trees, while Sileshi (2014) suggests a minimum sample size of 50 trees.

Notwithstanding the above considerations, equations for estimating biomass and carbon stock are still the most frequently adopted tool, due to the possibility to develop biomass estimations from forest inventory data. A recent study from Forrester et al. (2017) provides generalized biomass equations for 24 European tree species, unfortunately, neglecting many Mediterranean species such as Stone pine. This species is native from the Mediterranean basin, covering about 750,000 ha (Fady et al., 2004), with a recent increasing expansion through forest restauration or farmland afforestation (Mutke et al., 2012). Its economic interest is high due to the production of edible nuts, with current retail prices close to 100 €/kg. In fact, it has been used for many centuries for cone production but also in the recovery of lowland areas and in the protection of coastal dunes (Mutke et al., 2012). Stone pine have a high level of phenotypic plasticity, is demographically widespread but shows a remarkably low genetic diversity (Mutke et al., 2005; Vendramin et al., 2008). It appears either in arid inland or coastal sea areas affected by salinity stress and can potentially help in mitigating desertification problems in these areas. As a moderately drought-tolerant species, it is also of great interest in afforestations in a context of climate change (Correia et al., 2010). At the present, Stone pine has attained a high ecological, recreational and landscape value (Mazza et al., 2011).

Site-specific biomass equations and expansion factors for Stone pine have already been developed from harvested trees collected in Italy by Cutini et al. (2013), in Spain by Montero et al. (2005), Ruiz-Peinado et al. (2011) and Portugal by Correia et al. (2010). In this study, the data collected from the above studies were integrated and expanded, originating the largest and a unique biomass dataset for Stone pine, which has been used to develop allometric biomass (both aboveground and belowground) equations for the species, along its ecological and geographical Mediterranean range. The study specific objectives are: (1) to compare biomass relationships between trees growing in different ecological regions and management contexts; (2) to develop a system of biomass equations for aboveground and belowground biomass for the Mediterranean Stone pine and (3) to quantify the sources of error in biomass estimates associated with the use of biomass equations developed beyond their ranges of stand, site and climate conditions.

2. Material and methods

2.1. Data organization

The dataset contains biomass information obtained in harvested trees from three Mediterranean countries: Italy (IT), Portugal (PT) and Spain (SP) which were sampled in previous studies (Cutini et al., 2013; Ruiz-Peinado et al., 2011; Correia et al., 2010), either for aboveground and belowground biomass and also new data which have been collected under the current study. The final dataset contains measurements carried out in 283 trees, sampled in 16 sites located across the species' geographical range (Fig. 1).

For each country, the published studies contain a detailed description of the sampling protocol used for harvesting,measuring tree biomass and separating total biomass into different components. The sampling procedures are considered comparable between the countries regardless small differences related with the separation of branches by dimensions; bark separation from the trunk; and inclusion of thin roots. Each country used the same methodology for the belowground quantification, by removing the stump and roots within an area of approximately the crown projection, however for Spain the thin roots were not included.

Tree information regarding the diameter at breast height (d) and total height (h) was available for all sites (Table 1), with exception of Almonte site in Spain where tree height (h) was not measured. Total aboveground biomass (wa) was available for all sites, and corresponds to the sum of the tree aboveground components: stem, that includes wood and bark (ws) and excludes the stump not removed from the soil; branches (wbr) and needles (wl). Belowground biomass (wr), corresponding to the tree root system that includes the stump, was only available in some sites, for a total of 74 trees (Table 1). Stand data include stand age (t), stand density (N), mean temperature (T, in °C) and mean precipitation (P, in mm) (Table 1). No quantitative measurement of the stand density was available for the Spanish sites (SP) with only the information of tree competition within each stand by expert assessment.

2.2. Development of a system of biomass equations suitable to the whole Mediterranean region

A new system of equations was developed using the Mediterranean dataset collected from the three Mediterranean countries. Some trees were excluded because not all the tree components were available in some of the sites, namely tree height in Almonte and needle biomass in Roman Coast (see Table 1). The selection of the harvested trees was performed taking into consideration the diameter and approximate age classes distribution. Some trees were harvested from the same site. The equation used to model each tree biomass component was:

$$w = kd^{\alpha}x^{\beta} + \epsilon$$

where w is the total aboveground biomass or one of its component (branches, needles, stem or roots), k is the allometric constant, α and β are the allometric parameters, d is the tree diameter at breast height, x is an additional tree variable or a combination of variables and ϵ is the