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Local and general above-stump biomass functions for loblolly pine and slash pine trees

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A B S T R A C T

There is an increasing interest in estimating biomass for loblolly pine (*Pinus taeda* L.) and slash pine (*Pinus elliottii* Engelm. var. *elliottii*), two of the most ecologically and commercially important tree species in North America. The majority of the available individual-tree allometric models are local, relying on stem diameter outside bark at breast height (dbh) and, in some cases, total tree height (*H*): only a few include stand age or other covariates. Using a large dataset collected from five forestry research institutions in the southeastern U.S., consisting of biomass measurements from 744 loblolly pine and 259 slash pine trees, we developed a set of individual-tree equations to predict total tree above-stump biomass, stem biomass outside bark, live branch biomass and live foliage biomass, as well as functions to determine stem bark fraction in order to calculate stem wood biomass inside bark and stem bark biomass from stem biomass outside bark determinations. Local and general models are presented for each tree attribute. Local models included dbh or dbh and *H* as predicting variables. General models included stand-level variables such as age, quadratic mean diameter, basal area and stand density. This paper reports the first set of local and general allometric equations reported for loblolly and slash pine trees. The models can be applied to trees growing over a large geographical area and across a wide range of ages and stand characteristics. These sets of equations provide a valuable alternative to available models and are intended as a tool to support present and future management decisions for the species, allowing for a variety of ecological, silvicultural and economic applications, as regional assessments of stand biomass or estimating ecosystem C balance.

1. Introduction

The southern pines are among the most studied forest trees in the world, and have significant commercial and ecological value. In the southeastern United States there are approximately 83 million ha of timberland and more than 28 million ha of southern pine forests, from which 15 million ha corresponds to southern pine plantations (Wear and Greis, 2012). This forested area produces about 58% of the total U.S. timber harvest and about 18% of the global supply of industrial roundwood, making this region one of the most important timber production zones in the world (McKeand et al., 2003; Allen et al., 2005; Fox et al., 2007). In this region, slash pine (*Pinus elliottii* Engelm. var. *elliottii*) has been planted on more than 4.2 million ha, covering a wide range from eastern Texas to southern North Carolina to south-central Florida, with 79% of the planted slash pine occurring in Florida and Georgia (Barnett and Sheffield, 2005). Loblolly pine (*Pinus taeda* L.) grows on a variety of site types from east Texas to southern Tennessee to north Florida to southern New Jersey, and is one of the fastest growing pine species, planted in more than 10 million ha in the southeastern U.S. (Wear and Greis, 2012; Huggett et al., 2013). Both species has also been introduced into many countries and large-scale plantations for timber production are found in Argentina, Australia, Venezuela, Brazil, China, South Africa, New Zealand, and Uruguay (Barnett and Sheffield, 2005).

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Estimates of individual tree and component biomass are of interest to researchers, managers and policymakers (Jenkins et al., 2003). Measures of above-ground biomass are needed for estimating site productivity, and stand and tree growth and yield (Madgwick and Satoo, 1975). In addition, crown biomass estimates, together with harvesting techniques, determine the amount of logging residues and fire load, are necessary for planning prescribed fire and accounting for biomass for bioenergy production (Johansen and McNab, 1977; Hepp and Brister, 1982; Peter, 2008). Soil scientists and ecologists are also interested in quantifying biomass removals due to harvests, as they are concerned with its effects on site productivity and nutrient depletion (Powers et al., 1996; Shan et al., 2001; Sanchez et al., 2006). Ecologists are also interested in accurate estimations of stand biomass to analyze the effects of age and management on forest productivity (Ryan et al., 2006; Tang et al., 2014). In terms of greenhouse emissions mitigation, the forests in the southeastern and south-central U.S. could potentially capture CO_2 equivalent to about 23% of regional emissions (Han et al., 2007). The productivity and ubiquity of loblolly and slash pine make them key components of the carbon (C) balance of the United States. Hence, accurate estimates of tree biomass are central to our ability to understand and predict forest C stocks and dynamics (Galik et al., 2009; Johnsen et al., 2013).

Often, local functions used to estimate tree biomass rely on the stem diameter over-bark at breast height (dbh) (Swindel et al., 1979; Gholz and Fisher, 1982; Van Lear et al., 1984; Naidu et al., 1998; Jokela and Martin, 2000; Jenkins et al., 2003), or dbh and total tree height (*H*) as explanatory variables (White and Pritchett, 1970; Taras and Clark, 1975; Lohrey, 1984; Van Lear et al., 1986; Baldwin, 1987; Pienaar et al., 1987, 1996). These models are widely used but limited to certain stand characteristics and geographical areas, particularly those from which the data originated. However, inclusion of additional stand variables in these models such as stand age, density and/or productivity may improve the relationships, resulting in general models that provide more accurate predictions (Brown, 1997; Schmitt and Grigal, 1981; Alemdag and Stiell, 1982; Baldwin, 1987; Pienaar et al., 1987, 1996; António et al., 2007; Gonzalez-Benecke et al., 2014a). In addition, general models allow for better predictions on interpolation and extrapolation, allowing for more robust biological interpretation of the relationships under study because they account for the interaction between stand conditions and tree allometry.

Few general models are available in the literature that predicts above-stump biomass for loblolly (Baldwin, 1987; Pienaar et al., 1996) and slash pine trees (Pienaar et al., 1987). Those models, developed to predict stem component biomass, include only age, in addition to dbh and *H*, as predictors. Geographically generalized models are predictive equations fitted from data combined from many regions rather than a single location, such as site-specific biomass equations, and are generally applicable over the complete range of the aggregate data sources (Schmitt and Grigal, 1981). Using this geographically generalized approach, the objective of this study was to develop a set of individual-tree-level equations to estimate above-stump dry mass for different tree components for loblolly and slash pine trees, including local and general models that can be applied to trees of both species growing over a large geographical area and across a wide range of ages and stand characteristics, allowing for a variety of ecological, silvicultural and economics applications, from regional assessments of net primary productivity, to estimations of C budgets for life cycle analysis. The set of equations presented in this study provide a consistent basis for evaluations of southern pine forest biomass, improving the confidence in multi-scale analysis of C exchange between the forest and atmosphere.

2. Materials and methods

2.1. Data description

The dataset used to estimate the parameters for individual-tree above-stump biomass equations for loblolly and slash pine trees consisted of a collection of several sources used previously to publish site-specific allometric functions (Garbett, 1977; Manis, 1977; Gholz and Fisher, 1982; Gibson et al., 1985; Colbert et al., 1990; Baldwin et al., 1997; Albaugh et al., 1998Albaugh et al., 2004 Jokela and Martin, 2000; Adegbidi et al., 2002; Rubilar et al., 2005; Samuelson et al., 2004, 2008; Roth et al., 2007; Gonzalez-Benecke et al., 2010; Maier et al., 2012). The observations available corresponded to the raw data used for model fitting and not to the published equation estimates, as was the approach followed by Jenkins et al. (2003). This multi-source dataset was based on collaboration among five forestry research institutions in the southeastern U.S. Table 1 shows a summary of the number of trees measured by each institution for each species.

The dataset consisted of 744 loblolly pine and 259 slash pine trees measured at 25 and 14 sites, respectively. The data were collected across the natural range of the species distribution (Fig. 1), including trees from 2 to 36 years old, with dbh and *H* ranging between 1 to 35.6 cm and 1.5 to 25.7 m, respectively (Table 2). The data were collected under different management and stand development conditions, reflecting a variety of silvicultural inputs (planting density, soil preparation, fertilization, weed control and thinning), site characteristics (physiographic regions, soil type, and climate), genetics, rotations and developmental stage. The stand characteristics at the time of sampling were thought to integrate changes in allometry due to changes in silviculture, site quality and stand age. Details on site descriptions and sampling procedure can be found in each of the publications previously mentioned. In all cases, destructive sampling was carried out. Trees were selected to include the range of sizes encountered in each study. Fresh weight of all tree components was recorded *in situ*. Dry mass was computed after discounting moisture content determined on samples of all components after being oven-dried at 65–70 °C to a constant weight.

The dataset included tree-level attributes, including dbh (cm), *H* (m) and dry weight of each tree above-ground tree component: living foliage (FOLIAGE, kg); living branches (BRANCH, kg); stem outside bark (STEM, kg) and the whole-tree above-stump biomass (TASB, the sum of all components in kg). In a subset of the trees, STEM was partitioned into stem wood (WOOD, kg) and stem bark (BARK, kg) biomass, and a ratio between STEM and BARK (BFRAC) was determined. A comparison between species for the general relationships between dbh and above-stump biomass components is presented in Fig. 2.

The dataset included stand-level variables that characterized the plot where each selected tree was growing before being cut for biomass determination. The stand-level variables included were: basal area (BA, $m^2\ ha^{-1}$), trees per hectare (N, ha^{-1}) and stand age (AGE, years). Using N and BA, quadratic mean diameter (Dq, cm) was calculated and the ratio of dbh to Dq (Dp, $cm\ cm^{-1}$) was determined for each sampled tree. The variable Dp reflects the relative level of dominance of each tree within the plot. As site index (SI, m) was available for less than 30% of the whole dataset, that attribute was not included in the analysis. Stand-level variables associated with the 34 loblolly pine trees provided by Virginia Polytechnic Institute and State University were not available. Those trees were kept in the dataset as they provided valuable information due to the wide range in tree size and age, and were only used for fitting models that did not use stand-level variables. Details of tree and stand characteristics of the dataset used are summarized in Table 2.