Modeling the effects of forest management on *in situ* and *ex situ* longleaf pine forest carbon stocks [☆]

C.A. Gonzalez-Benecke [a,*], L.J. Samuelson [b], T.A. Martin [c], W.P. Cropper Jr. [c], K.H. Johnsen [d], T.A. Stokes [b], J.R. Butnor [e], P.H. Anderson [d]

[a] *Department of Forest Engineering, Resources and Management, 280 Peavy Hall, Oregon State University, Corvallis, OR 97331, USA*
[b] *School of Forestry and Wildlife Sciences, Auburn University, 3301 SFWS Building, Auburn, AL 36849, USA*
[c] *School of Forest Resources and Conservation, P.O. Box 110410, University of Florida, Gainesville, FL 32611, USA*
[d] *USDA Forest Service, Southern Research Station, 3041 Cornwallis Road, Research Triangle Park, NC 27709, USA*
[e] *USDA Forest Service, Southern Research Station, 81 Carrigan Drive, University of Vermont, Burlington, VT 05405, USA*

ABSTRACT

Assessment of forest carbon storage dynamics requires a variety of techniques including simulation models. We developed a hybrid model to assess the effects of silvicultural management systems on carbon (C) budgets in longleaf pine (*Pinus palustris* Mill.) plantations in the southeastern U.S. To simulate *in situ* C pools, the model integrates a growth and yield model with species-specific allometric and biometric equations and explicitly accounts for the impacts of both thinning and prescribed fire. To estimate the *ex situ* C pool, the model used the outputs of merchantable products from the growth and yield model with current values of forest product conversion efficiencies and forest product decay rates. The model also accounts for C emissions due to transportation and silvicultural activities. Site productivity (site quality) was the major factor controlling stand C density followed by rotation length. Thinning reduced C sequestration, as the slow growth rate of longleaf pine reduced the potential of C sequestration in forest products. Prescribed burning reduced average C stock by about 16–19%, with the majority of the reduction in the forest floor. In a comparison of longleaf pine C dynamics with slash pine (*Pinus elliottii* Engelm.), both species reached a similar average C stock at age 75 years, but when averaged across the whole rotation, slash pine sequestered more C. Nevertheless, for medium quality sites, C sequestration was similar between thinned 75-year rotation longleaf pine and unthinned 25-year rotation slash pine. This longleaf pine plantation C sequestration model, based on empirical and biological relationships, provides an important new tool for developing testable research hypotheses, estimating C stocks for regional assessments or C credit verification, and for guiding future longleaf pine management.

© 2015 Elsevier B.V. All rights reserved.

1. Introduction

Atmospheric carbon dioxide (CO_2) mitigation requires an approach that combines increasing terrestrial carbon (C) storage with CO_2 emission reductions (Sundquist et al., 2008). Forests and forest management play an important role in the mitigation of atmospheric CO_2 through the fixation of atmospheric CO_2 into plant tissue (Sedjo, 1989, 1997; Nabuurs, 2007). In the United States (U.S.), forests represent over 90% of the terrestrial C sink, which is equivalent to 12–16% of annual U.S. greenhouse gas (GHG) emissions (U.S. EPA, 2005). Southeastern U.S. forests contain 36% of the C sequestered in the contiguous U.S. (Turner et al., 1995), and these forests have the potential to sequester even more C via improved sustainable forest management (Johnsen et al., 2014).

Longleaf pine (*Pinus palustris* Mill.) was once a dominant forest type in the southeastern U.S., ranging from Virginia to Florida and Texas, but, due to logging and conversion to agriculture and other forest types, only about 1.2 million ha of longleaf pine forest remain (Frost, 2006). As part of the effort to restore longleaf pine ecosystems, longleaf pine is being planted in even-aged plantations. Currently there are approximately 0.4 million ha of longleaf pine plantations (Woudenberg et al., 2010). Longleaf pine is considered a slower growing species than loblolly (*Pinus taeda* L.) and slash (*Pinus elliottii* Engelm.) pines, the two other major commercial southern pines, but its relative longevity offers opportunities to sequester C in offset projects with longer contracts (Samuelson et al., 2014).

Longleaf pine planted for ecosystem restoration is often established at lower tree densities than other southern pines, and this often results in a more abundant and diverse ground cover community that is typically managed with prescribed fire. Prescribed burning is an important management tool in longleaf forests, with recommended burning frequencies of at every two to four years (Chapman, 1932; Glitzenstein et al., 1995, 2003; Loudermilk et al., 2011). Prescribed burning is mainly used to control competing vegetation, favoring pine regeneration and increasing diversity and productivity of herbaceous plants (Haywood, 2007). Without frequent fire, longleaf forests typically succeed into hardwood dominated forests (Quarterman and Keever, 1962; Hartnett and Krofta, 1989; Mitchell et al., 2006). Thus, the role of frequent prescribed fire in carbon dynamics is important to assess. Fire volatilizes carbon, but may not represent a significant loss over a long rotation due to rapid recovery of biomass following fires.

The goal of this study was to develop a model that can be used to analyze the effects of silviculture on C budgets in longleaf pine plantations in the southeastern U.S. To simulate *in situ* C pools, we developed a hybrid model that integrates a growth and yield model for longleaf pine (Gonzalez-Benecke et al., 2012) with allometric and biometric equations determined for the species (Baldwin and Saucier, 1983; Gonzalez-Benecke et al., 2014; Samuelson et al., 2014). To estimate *ex situ* C pool dynamics, the model used the outputs of merchantable products from the growth and yield model and current values of forest product conversion efficiencies and forest product decay rates (Gonzalez-Benecke et al., 2010a, 2011). The model also simulated the C emissions of transportation and silvicultural activities of the various tested scenarios (Markewitz, 2006). Considering current and potential new management schemes, we used to the model to determine: (1) the degree to which site index and different management regimes, incorporating longer rotations and thinning, maximize accumulation of C *in situ* and *ex situ* pools; (2) how much prescribed burning reduces time-averaged C stocks; and (3) if C accumulation over longer rotations is comparable to slash pine, a more intensively managed southern pine species.

2. Materials and methods

All models used to estimate stand growth and biomass dynamics were based on longleaf pine datasets. Forest floor decay rate and *ex-situ* forest products functions were derived from slash pine publications. Emissions of transportation and silvicultural activities were assumed to be species independent, so we used the standards reported for loblolly pine.

2.1. Models

Growth and yield models were combined with allometric and biometric equations to estimate C fluxes and stocks. We used a longleaf pine growth and yield model reported by Gonzalez-Benecke et al. (2012). The model predicts stand growth in basal area (BA, $m^2\ ha^{-1}$), total volume (V, $m^3\ ha^{-1}$), dominant height (Hd, m), quadratic mean diameter (QMD, cm) and number of surviving trees (Nha, trees ha^{-1}), using as inputs site index (SI, m), and number of trees at planting (PD, trees ha^{-1}).The reference age for SI of longleaf pine was 50 years. The model can also simulate thinnings, where the user defines a thinning scheme that can be described by timing and intensity (by defining age and removal percentage), or by target BA (by defining target maximum BA that triggers the thinning and residual BA after thinning). From the original set of equations reported by Gonzalez-Benecke et al. (2012), the function to estimate survival was modified to include Reinecke's stand density index (SDI, trees ha^{-1}) as a covariate. The new model showed

better fit and prediction accuracy than the model reported Gonzalez-Benecke et al. (2012), especially for mature and thinned stands. Table 1 presents a list of functions used for growth and yield modeling.

Using the data reported by Gonzalez-Benecke et al. (2012), we fit new models to estimate survival of planted longleaf pine trees. The dataset consisted of 267 plots regularly remeasured and maintained by the U.S. Forest Service's Laboratory at Pineville, LA. Each plot was measured for ∼40 years at ∼five-year intervals, averaging eight measurements per plot. Plantation ages ranged between 7 and 73 years; BA ranged between 6.6 and 55.9 $m^2\ ha^{-1}$; and SI ranged between 19.6 and 30.8 m (Gonzalez-Benecke et al., 2012). A negative-exponential survival model that includes Hdom and SDI was used to estimate survival using a modified version of the model proposed by Zhao et al. (2007) and Gonzalez-Benecke et al. (2012):

$$Nha_2 = Nha_1 \cdot e^{\left[\left(a_1\frac{H_{dom_i}}{100} + a_2 \cdot SDIr_i\right)\cdot\left(Age_2^{a_3} - Age_1^{a_4}\right)\right]} + \varepsilon_1$$

where Nha_j is the number of trees ha^{-1} at age j (yr), Nha_i is the number of trees ha^{-1} at age i (yr) ($i < j$), H_{dom_i} is the dominant height (m) at age i (yr), $SDIr_i$ is the relative SDI at age i (yr), a_1 to a_4 are curve fit parameter estimates, SDIr is the SDI relative to a maximum observed of 1111 trees ha^{-1} (Gonzalez-Benecke et al., 2012) and ε_1 is the error term, with $\varepsilon_1 \sim N(0, \sigma_1^2)$.

At each age, allometric equations were used to estimate aboveground and belowground biomass. For belowground biomass we used the model reported by Samuelson et al. (2014). For aboveground biomass, we fitted new models to the data reported by Baldwin and Saucier (1983). We had access to the raw dataset that consisted of 111 trees sampled in 10 unthinned stands in Louisiana and Texas, with age ranging between 10 and 44 years, and dbh ranging between 2.8 and 52.3 cm (Baldwin and Saucier, 1983). The dataset included tree-level attributes, including dbh (cm), height (m) and dry weight (kg) of each tree aboveground tree component: living foliage, living branches, stemwood, stembark, stem outside bark (stem, the sum of stemwood and stembark), and the whole-tree aboveground biomass (TAGB, the sum of all components). The models selected to estimate aboveground biomass were:

$$TAGB, branch, stem, stemwood, stembark = b_1 \cdot (dbh^{b_2}) \cdot (Height^{b_3}) + \varepsilon_2$$

$$Foliage = b_1 \cdot (dbh^{b_2}) \cdot (Height^{b_3}) \cdot (Age^{b_4}) + \varepsilon_2$$

where b_1 to b_4 are curve fit parameter estimates and ε_2 is the error term, with $\varepsilon_2 \sim N(0, \sigma_2^2)$. At each age, stand biomass was calculated by multiplying Nha, estimated by the growth and yield model, by the individual-tree biomass estimated with the fitted functions, using QMD as a surrogate of dbh and the mean height estimated using the model shown in Table 1 (reported by Gonzalez-Benecke et al., 2014).

At each age, mean yearly projected LAI of the longleaf pine overstory was estimated as the product between foliage biomass and the specific needle area (SNA, $m^2\ kg^{-1}$). Using data collected by Samuelson et al. (2012, 2014 and unpublished), Samuelson and Stokes (2012) and Gonzalez-Benecke et al. (2010b), the relationship between age and SNA was determined by fitting the following model:

$$SNA = c_1 + c_2 \cdot e^{(-c_3 \cdot AGE)} + \varepsilon_3$$

where c_1 to c_3 are curve fit parameter and ε_3 is the error term, with $\varepsilon_3 \sim N(0, \sigma_3^2)$.

Annual needlefall (NF, Mg ha^{-1} $year^{-1}$) was assumed to correspond to half of foliage biomass of the previous year. The needlefall/litterfall ratio model reported by Gonzalez-Benecke et al.