Projecting Carbon Pools in Aboveground Woody Accumulations and Harvested Wood in Loblolly Pine Plantations of the Southern United States: From Stand-level to Regional Scales

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ABSTRACT

Accounting for in-woods carbon storage in carbon accounting systems may be insufficient when substantial amounts of sequestered carbon are harvested and converted to long-lived wood products and landfills. The potential for offsetting greenhouse gas (GHG) emissions by storing carbon in managed loblolly pine forests in the southern United States was projected over the next half-century, both in terms of in-woods aboveground carbon pools and harvested products, including wood used for energy production. A region-wide data set from the Forest Inventory Analysis (FIA) program of USDA Forest Service was used to set initial conditions and estimate model parameters for projecting management activities including plantation area, age distributions of thinning, and clearcut harvest on an annual timestep. The stand-level growth and yield model FASTLOB was linked to the FIA data to project growth rates and annual harvest volumes of sawtimber and pulpwood for the projection period, accounting for annual timber harvests and the life cycles of wood products. In addition to baseline management practices, projections were made for scenarios that assumed increasing management intensities including the use of chemical fertilizers and herbicides and genetically-improved growing stock. Present-day carbon storage in well-managed southern pine plantations averaged 30.54 $\text{Mg}\cdot\text{ha}^{-1}$ (± 2.54%) for aboveground carbon. Over a 50-year projection, annual wood production was 62.1 and 45.9 million green metric tons from pulpwood and sawtimber yield, with roughly one-fourth of the green weight being carbon. Baseline projections showed aboveground carbon pools of up to 341 million metric tons being maintained over the next 50 years, with 93% in aboveground live trees and 7% in coarse woody debris (CWD). The carbon storage in wood products increased steadily over the half-century projection and showed no sign of leveling off, while the storage in plantations was found to remain constant or increase slightly over time. An additional 11 million metric tons of harvested carbon was used for energy per year on average, equivalent to 25% of annual forest-products-industry renewable energy use in U.S.A. Intensified forest management practices showed the potential to increase as much as 30% total carbon stored in in-woods and harvested-wood-products pools, with potential increases up to 40% in energy offsets above the baseline scenario. Reducing management intensity greatly increased in-woods carbon storage potential, but eliminated the wood-products carbon sink.

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List of Abbreviations

BTU	British thermal unit
CWD	coarse woody debris
DEM	digital elevation model
ECDF	empirical cumulative distribution function
FIA	Forest Inventory Analysis
GHG	greenhouse gas
MC	moisture content
TPO	timber product output
USDA	U.S. Department of Agriculture

Introduction

Forest ecosystems in the United States sequester 140-300 million metric tons (Mg) of carbon per year, or between 18% and 39% of the equivalent CO_2 emissions from the Nation's coal-fired power plants (Pacala *et al.*, 2001; Heath and Smith, 2004; U.S. Environmental Protection Agency, 2007b). Despite scientists' knowledge that U.S. forests are an important terrestrial carbon sink, challenges remain in estimating the magnitudes of carbon storage attributed to forests in different geographic regions and in quantifying the magnitudes of fluxes for various forest carbon pools (Houghton *et al.*, 1999; Schimel *et al.*, 2000; Pacala *et al.*, 2001; Janssens *et al.*, 2003). One challenge involves incorporating uncertainty into estimates, so that decision-makers can plan in accordance with the quality of information in-hand (Gong, 1998; McKenney *et al.*, 2004). Another challenge is to account for carbon sequestered in wood removed from forests as wood and paper products that may persist for long periods of time (Skog and Nicholson, 1998; Perez-Garcia *et al.*, 2005). Such information is generally not a standard component in forest carbon estimates (Heath *et al.*, 2003); however, both concerns are essential in making decision or plans for managed forest ecosystems, including the loblolly pine (*Pinus taeda* L.) plantations extensive throughout the southern United States.

Carbon stored above ground in loblolly pine plantations includes both merchantable and non-merchantable trees and vegetation, along with dead wood and plant detritus (Smith *et al.*, 2004a). Regarding "long-lived" aboveground carbon pools, i.e. those in which carbon remains sequestered for decades or more, separate accounting is often made for live trees and coarse woody debris (CWD) based on the differing biological and ecological processes acting on each. Live trees sequester carbon on temporal scales of several decades, corresponding to rotation lengths. Carbon in CWD may persist in forests for years to decades depending on the relative rates of accumulation and decomposition (Duvall and Grigal, 1999; Vanderwel *et al.*, 2008; Radtke *et al.*, 2009). While aboveground carbon stored in live trees can be reliably assessed and projected over time and space, accumulations of CWD are considerably variable across landscapes and depend significantly on disturbance and management (Duvall and Grigal, 1999; Fridman and Walheim, 2000; Campbell *et al.*, 2008).

In evaluating the potential of managed forest ecosystems such as loblolly pine plantations in mitigating atmospheric GHG accumulations from the burning of fossil fuels, accounting for carbon stored in live trees and CWD is insufficient because substantial amounts of sequestered carbon are harvested and converted to end-use wood products, e.g. building materials, furniture, and paper products, or used as a fuel source to displace GHG emission from fossil fuels (Birdsey and Heath, 1995; Smith *et al.*, 2006). Although harvested wood is not a part of in-woods carbon pools, the linkages between management activities, forest carbon sequestration, and the timing and amount of wood harvested are inextricable. Wood products may persist longer than plantation rotation lengths, and the amount of carbon remaining in wood products – products in use and landfills – contributes significantly to carbon sequestration over time (Skog and Nicholson, 1998). Moreover, the magnitudes and rates of carbon remaining in wood products depend on the timing, intensity, and extent of harvesting activities, which affects what products the harvested wood is allocated to and life spans of wood in these products. On the other hand, wood processing at mills, e.g. drying, peeling, slicing, and sawing, uses energy from burning wood residues and pulping liquors that reduces some need for using fossil fuels. Such energy sources currently supply 1.5% of the total energy consumption in the U.S.A. (Perlack *et al.*, 2005). Compared to the combustion of fossil fuels, bioenergy from harvested wood is relatively carbon-neutral and can be renewable (Schiermeier *et al.*, 2008). Reliable accounts of long-term carbon mitigation potential from these managed ecosystems should not fail to take harvested carbon into account (Smith *et al.*, 2006). As demand for wood products grows, so too will plantation management intensity. Both factors will likely impact the amount of atmospheric carbon sequestered in southern U.S. forests and the wood products derived from them. Effective policy-making, planning, and management will require good information to ensure that these factors are accurately accounted for in optimizing carbon sequestration that can be supported by southern U.S. forests (Wear and Greis, 2002).

Plantation management in the U.S. South is expected to increase in intensity in order to provide more raw materials to meet rising societal demands for wood resources (Prestemon and Abt, 2002). Loblolly pine plantations comprise 9.7 million hectares of southern U.S. timberland, roughly 65% of the southern plantation area, and their area is projected to increase by 67 percent in the next thirty years (Prestemon and Abt, 2002; Wear and Greis, 2002; Smith *et al.*, 2004c). Through woody and herbaceous vegetation control and fertilization, site characteristics are being actively managed to enhance productivity (Allen, 2001). Intensive site preparation, including bedding, disking, subsoiling, ripping, or combinations of these treatments, can efficiently reduce competition from non-commercial hardwood species (Morris and Lowery, 1988). In addition, herbicide application can improve seedling establishment and early growth (Nilsson and Allen, 2003). Fertilization has become an important silvicultural tool in treating nutrient-deficient midrotation stands for increasing volume growth (Fox *et al.*, 2007). Planting genetically-improved growing stock has become a standard management tool to increase growth efficiency, with gains in volume growth averaging 10 to 30% over unimproved planting stock at harvest (Li *et al.*, 1999; McKeand *et al.*, 2003). Tree breeding and other efforts to improve genetic properties of plantation growing stock are increasingly producing commercially available families and genotypes for increased volume production in loblolly pine (McKeand *et al.*, 2003; Allen *et al.*, 2005; McKeand *et al.*, 2006). Intensive management operations appear to have potential for sequestering greater carbon, and projections of management scenarios will provide an insight on dynamics of in-woods and products-based carbon pools.

Recently, national-scale inventory-based carbon assessments have been augmented to account for carbon stored in aboveground forest pools, as well as the carbon stored in wood products (Skog and Nicholson, 1998; Heath *et al.*, 2003; Jenkins *et al.*, 2003; Smith *et al.*, 2003). To date, such assessments have not directly considered the resolution, intensity, nor timing of management activities prescribed at forest stand scales. Because management is typically carried out on the scale of forest stands, carbon accounting at the same scale will allow for tracking of the full range of management and harvesting activities (Harmon, 2001). In addition, stand-level accounting can be scaled up with increasing certainty, while downscaling of national-scale estimates generally leads to greater uncertainty (Freese, 1967; Smith *et al.*, 2004a). Here, predictions will be made at the resolution of individual forest stands for greatest flexibility in prescribing management conditions. Results will be aggregated to state and regional scales to make broader geographic assessments, presumably with a relatively high degree of precision (Smith *et al.*, 2004a). The resulting analyses should serve the information needs of individuals ranging from those who develop policies for climate change mitigation, to those who set long-term regional goals for carbon sequestration, to those who aim to increase the total carbon stored in the wood grown on and products harvested from their forest lands.

Objectives

The goal of this research was to assess impacts of forest management on carbon storage in loblolly pine plantations across the southern United States over the next half-century. Of specific interest here are the in-wood carbon pools of aboveground live tree and CWD, and pools of carbon in wood products produced from southern forests. To preserve information related to stand-level management activities, extensive field-plot inventory data were coupled with stand-level prediction models to reduce uncertainty in estimates and facilitate aggregation across different spatial and temporal scales. Four specific objectives were pursued as a part of the overall goal:

Objective 1 Estimate the amount of carbon stored aboveground in live trees and CWD at scales ranging from individual stands to the entire southern United States.

Objective 2 Predict the annual production of harvested wood under operational management over a 50-year span, distinguishing between wood harvested for use in solid wood and paper products, and accounting for trends related to management intensity;

Objective 3 Project in-woods carbon pools and carbon disposition in harvested wood over a 50-year time span, linking inventory-based data and management activities to existing models of growth and yield and accounting for the lifespan of wood products;

Objective 4 Evaluate long-term effects of intensive management of loblolly pine in the U.S. South, including competing vegetation control, fertilization, and planting of genetically improved growing stock, on carbon sequestration and storage.

Coarse Woody Debris in Southern United States Loblolly Pine Plantations: From Stand-level to Regional Scales

Abstract

Broad-scale estimates of coarse woody debris (CWD) yield across landscapes are somewhat rare, despite the importance of CWD in ecosystem functioning and its potential role in terrestrial carbon cycles. Yields of CWD were estimated at regional scales by linking a stand-level predictive model with regional forest inventory data for eleven states in the southern United States. We estimated that the accumulation of CWD in late-rotation loblolly pine plantations across the South totals 48.67 million metric tons of dry wood necromass, the carbon equivalent of 24.33 million metric tons. This represents 1.5% of total energy-consumed GHG emission, on a CO_2 equivalent basis, in the United States in 2006. Confidence intervals for CWD dry weight per hectare generally did not exceed ± 25% of the estimated values. Although county-level estimates were of higher uncertainty, the spatial pattern appeared to be relatively consistent with the extent of loblolly pine, with low yields near the extremes of the species' natural range and high yields in extensively-forested portions of its range. Quantifying regional carbon stores of CWD with respect to stand-level management activities may improve accuracy of regional estimates and provide further insight into management effects on the carbon pool and the carbon cycle.

Keywords: *Pinus taeda*; carbon sequestration; downed woody material; forest inventory; FIA

Introduction

Forest ecosystems in the United States sequester 140-300 million metric tons (Mg) of carbon per year, or between 18% and 39% of the equivalent carbon dioxide emissions from the Nation's coal-fired power plants (Pacala *et al.*, 2001; Heath and Smith, 2004; U.S. Environmental Protection Agency, 2007a). Despite scientists' knowledge that U.S. forests are an important terrestrial carbon sink, challenges remain in estimating the amount of carbon stored by forests in different geographic regions and in that stored in various forest carbon pools such as live trees and dead woody material (Houghton *et al.*, 1999; Schimel *et al.*, 2000; Pacala *et al.*, 2001; Janssens *et al.*, 2003). Accounting for effects of forest management practices on carbon storage over time poses additional challenges, partly due to the implementation of forest management operations on finer temporal and spatial scales than are generally accounted for in regional carbon budgets (Schulze *et al.*, 2000). This concern is especially relevant to managed forest ecosystems, including loblolly pine (*Pinus taeda* L.) plantations that are common in the southern United States.

Loblolly pine forests cover 21.9 million hectares of U.S forestland, roughly 25% of the area of southern forests (Smith *et al.*, 2004c). While the species is grown commercially in the U.S. primarily in the South, its range is sufficiently broad to have considerable economic impact in at least eleven southern states (Figure 1) (Little, 1971; Wear and Greis, 2002). Due to the species' value for wood and fiber production, roughly 9.7 million hectares of southern U.S. lands currently support loblolly pine grown in plantations (Smith *et al.*, 2004c). Intensive management regimes are practiced increasingly across the loblolly pine land base, resulting in corresponding increases in annual wood production (Schultz, 1997; Wear and Greis, 2002; Allen *et al.*, 2005). Although the effects of intensive management on stand growth and yield have been widely studied, research is somewhat limited on the potential of intensive management for affecting the partitioning of carbon stored in different forest carbon pools (Jokela *et al.*, 2004; Amateis and Burkhart, 2005; Miller *et al.*, 2006). Precise estimates of individual carbon pools serve as a critical component for accurate carbon accounting that seeks to track forest management effects on carbon storage in plantations.

Coarse woody debris (CWD) is a major component of aboveground necromass, contributing to a variety of ecosystem services including species diversity, water quality, nutrient cycling, and carbon storage (McMinn and Crossley, 1996; Krankina *et al.*, 1999). Despite the importance of CWD in ecosystem functioning and its potential role in terrestrial carbon cycles, broad-scale estimates of CWD accumulations across landscapes are somewhat rare (Spetich *et al.*, 1999; Krankina *et al.*, 2002; Applegate, 2008). Precise estimates of CWD production and yield are difficult to obtain because of their dependencies on environmental factors including disturbance, climate, soil moisture, and topographic gradients (Spies *et al.*, 1988; Marra and Edmonds, 1994; Rubino and McCarthy, 2003). Amounts of CWD vary considerably across landscapes depending on ecological factors such as forest type, mortality and wood decomposition rates, and developmental or successional stages (Fridman and Walheim, 2000; Herrmann and Prescott, 2008). The mass of CWD in forest stands does not always parallel the biomass of living trees, posing challenges for inventory-based estimates (Smith *et al.*, 2003). Hence, broad-scale estimation across landscapes may be subject to considerable uncertainty when extrapolating results from studies made under different environmental or ecological conditions.

Inventory-based approaches to assessing CWD amounts are limited by the time- and labor-intensive nature of sampling methods. Sampling CWD is generally subject to considerable variation and requires high sampling intensities, with little or no correlation between CWD mass and most timber-based attributes (Chojnacky and Heath, 2002; Smith *et al.*, 2003; Applegate, 2008). Despite these challenges, CWD measurements have been included as a part of the national Forest Inventory and Analysis (FIA) program of the U.S. Department of Agriculture (USDA) Forest Service since 2001 (Woodall and Monleon, 2008). The FIA survey design is carried out in three phases, with Phase I involving aerial photo or image interpretation to distinguish between forested and non-forested land areas. Phase II involves the establishment of field plots on a sampling grid of roughly one plot per 2,428 hectares (6,000 acres). Phase III plots are installed at 1 of every 16 Phase II plot locations (Forest Inventory and Analysis, 2009b). Phase III observations include the estimation of downed woody material by line-intercept sampling. Because of the relatively low sampling intensity of Phase III plots, estimates of CWD from FIA inventories are typically subject to greater sampling errors than estimates based on Phase II data (Woodall and Monleon, 2008).

It is well known that intensive management affects the production and yield of CWD in forests (Duvall and Grigal, 1999; Fridman and Walheim, 2000). For example, Radtke et al. (2009) determined that thinned loblolly pine forests produced only between 12% and 22% as much CWD as their unthinned counterparts. Accounting for variables related to forest management activities, e.g., stand age, stem density, and site productivity, along with information about silvicultural prescriptions such as thinning, may increase the precision of CWD mass estimates in loblolly pine plantations in the southern United States.

One way to improve the accuracy of regional-scale assessments of CWD is by linking stand-level models with regional inventory data. Stands span the full range of stages in forest management regimes, affecting temporal and spatial distributions of forest carbon pools. Given the availability of a CWD yield model driven by stand-level variables, the amount of CWD accumulated in a particular stand can be predicted from readily available inventory data. By applying such a model at stand levels, the effects of stand conditions, site quality, and management practices on CWD production can be directly accounted for (Radtke *et al.*, 2009). Regional-scale carbon stored in CWD can then be estimated through aggregating stand-level yields of CWD to regional scales of interest and converting wood dry mass to carbon content (Harmon, 2001).

The overall objective of this study was to quantify the accumulated mass and carbon content of CWD – what we refer to as CWD yield – in late-rotation loblolly pine plantations across the southern United States. To achieve this objective, a stand-level empirical model of CWD mass yield was linked to regional forest inventory data from the U.S. Forest Service's FIA Phase II field data. The FIA inventory data were used to generate CWD mass yield predictions at stand-levels, with the stand-level predictions then aggregated to county, state, and southwide extents based on FIA estimates of forest area. An additional goal was to obtain variance and confidence interval estimates to assess the magnitudes of uncertainty associated with CWD mass estimates.

Materials and Methods

Data

Forest inventory data from the USDA Forest Service's FIA program were used as the source of information for stand-level conditions in southern U.S. loblolly pine plantations. Phase II inventory data were obtained (Forest Inventory and Analysis, 2009a), from 2005 – 2007 survey data for Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, Texas and Virginia (Figure 1). The FIA data were screened to identify conditions consistent with loblolly pine plantations characterized by Radtke et al. (2009) in the development of their CWD yield model. Stand origin was limited to artificial regeneration of loblolly pine, with plantation ages limited to a range between 15 and 45 years, an age condition we refer to as “late-rotation” for loblolly pine plantations. Silvicultural practices were restricted to thinning or no observable treatment, i.e. stands where nonstandard silvicultural practices such as pruning or girdling were excluded. Of 539 counties across the study region, a set of 2,829 FIA inventory plots matched the screening conditions, including 1,715 plots on which the screened condition was observed on the entire plot, and 1,114 on which the screened condition was observed on a portion of the plot (Forest Inventory and Analysis, 2009a).

Stand and regional-level CWD estimates

Equation [1], which was developed by Radtke et al. (2009), was used to predict stand-level total CWD mass (TCWD, Mg·ha^{-1}) based on field observations for each of the 2,829 full or partial FIA Phase II plots. The geographic range of data used by Radtke et al. (2009) in developing [1] spanned much of the range of planted loblolly pine (Figure 1). Their data included some 1,360 plot-level estimates of CWD yield, with 62% from thinned plots. Stand ages varied from 11 to 45 years with a mean of 26.9 years. Density in the late-rotation plantations ranged from 185 to 2,196 stems·ha^{-1}, and site index ranged from 14 to 25 m at base age of 25 years. In more than 95% of FIA plots used here, stand ages, densities, and site index were all within these variables’ ranges from the data used to fit the regression model [1]. Using the same definition as the prediction equation, TCWD was limited to dead woody material having diameters ≥ 7.6 cm (3.0 in) at breast height for snags (standing dead trees) or at the large-end cross-section for logs (dead and downed tree stems). Also according to the model’s definition, TCWD yield was limited to dead wood produced by plantation crop trees during a single rotation, excluding sources such as non-planted trees or CWD remaining from past rotations.

$$\widehat{\ln(TCWD)} = -8.447 - 1.750Z + 1.999\ln(A) - 0.00116N + 1.546\ln(HD) \qquad [1]$$

where

$$Z = \begin{cases} 1 \text{ for previously thinned plantations} \\ 0 \text{ for unthinned plantations} \end{cases}$$

A = plantation age (years)

N = stand density (trees·ha^{-1})

HD = average height of dominant and codominant trees (m)

To obtain unbiased estimates for TCWD on the non-logarithmic scale, the correction suggested by Baskerville (1972) was used

$$\widehat{TCWD} = \exp\left\{\widehat{\ln(TCWD)} + \hat{\sigma}^2/2\right\} \qquad [2].$$

with $\hat{\sigma}^2 = 1.653$ specified as the standard error of predicted ln(TCWD) from [1] reported by Radtke et al. (2009).

Per-hectare TCWD was estimated for each FIA field plot using [1] and [2] with FIA Phase II data serving as model inputs. Area expansion factors from FIA Phase I for each plot were multiplied to the per-hectare estimates of TCWD in order to obtain aggregated totals for counties, states, and the entire eleven-state study area. To account for differences in forestland area among regions, means of CWD per hectare were obtained by dividing the regional aggregated CWD totals by the corresponding forestland areas for plantations meeting the screening criteria in either counties, states, or the entire study area.

Analysis

Aggregating stand-level CWD estimates to individual counties and states precluded the ability to calculate variance using FIA area expansion factors (Scott *et al.*, 2005); therefore, we used a bootstrap procedure to approximate sample variance and confidence intervals for regional estimates of CWD mass. A nonparametric approach was used to avoid the need to adopt a functional formulation for the CWD population distributions. The procedure generated 2,000 bootstrap samples of size 2,829, with replacement, from the FIA phase II plot data. From each bootstrap sample, aggregated CWD estimates were computed for all counties, all states, and the eleven-state region. Standard errors and the 2.5th and 97.5th percentiles for the confidence interval were then approximated from the bootstrap sample results.

Results

In managed loblolly pine forestland across the South, the estimated mass of CWD from planted trees in late-rotation plantations exceeded 48 million Mg (1 Mg = 1 metric ton or approximately 1.1 U.S. tons; Table 1). State-by-state CWD mass totals varied from 0.63 to 8.69 million Mg with the mean CWD mass per hectare of plantation forestland ranging from 6.45 to 13.31 $Mg \cdot ha^{-1}$ (Table 1). The largest CWD mass total and mean CWD mass per hectare in late-rotation plantation forestland were in North Carolina, which had only the fifth-largest area of late-rotation plantation forestland of the eleven states in the study area (Table 2). Late-rotation loblolly pine plantation ages in North Carolina were the oldest of the states considered, averaging 25.2 years on 653,304 hectares of forestland. Ages for late-rotation plantations in some other states, e.g., Georgia and Alabama, were considerably younger on average, despite their occupying more land area than those in North Carolina (Table 2).

Tennessee and Florida had the lowest CWD mass totals, largely due to their comparatively small areas of late-rotation plantation forestland. Fewer FIA plots were observed in loblolly pine plantations for Tennessee as well; therefore, its standard errors of estimated totals and means for CWD mass were relatively large compared to other states' estimates. Excepting Tennessee and Florida, 95% bootstrap confidence intervals for states' mean CWD $\mathrm{Mg{\cdot}ha^{-1}}$ in late-rotation plantation forestland did not exceed ± 25% of the estimated values (Table 1).

While the totals from the eleven states and means per hectare showed relatively symmetric distributions (state averages of 4.4 million Mg, and 8.5 $\mathrm{Mg{\cdot}ha^{-1}}$, respectively), predictions of stand-level TCWD from [1] and [2] showed a skewed distribution, with median 3.90 $\mathrm{Mg{\cdot}ha^{-1}}$, mean 8.61 $\mathrm{Mg{\cdot}ha^{-1}}$, and standard deviation 13.0 $\mathrm{Mg{\cdot}ha^{-1}}$. It follows that a large majority of stands had predicted CWD $\leqq$ 10 $\mathrm{Mg{\cdot}ha^{-1}}$ while a small number exceeded 100 $\mathrm{Mg{\cdot}ha^{-1}}$ (Figure 2). The skewed nature of this distribution is related to the distributions of predictors from FIA Phase II field plots and the magnitudes and signs of coefficients in the prediction equation [1]. In general, unthinned stands with low surviving N, and large A and HD produce the largest estimates of TCWD. Although the thinning status is not indicated for all the data shown in Figure 2, it is relevant to note that of the stands with predicted TCWD > 30 $\mathrm{Mg{\cdot}ha^{-1}}$, all but one represented unthinned plantations.

Aggregated estimates for counties across the South varied widely, ranging from 201 to 1,361,139 Mg of total CWD mass, and 0.80 to 80.05 $\mathrm{Mg{\cdot}ha^{-1}}$ for the mean CWD mass per hectare in plantation forestland (Figure 3, Figure 4). County-aggregated CWD mass totals averaged 90,306 Mg with a median 54,348 Mg, indicating that the distribution was considerably skewed. In other words, while most counties' CWD totals were less than about 100,000 Mg, a few had very high CWD totals exceeding 1,000,000 Mg. Bootstrap standard errors for county-level estimates ranged between 24% and 107% of the total CWD mass, with a median standard error of 63% for total CWD mass (Figure 5). Standard errors for county-level CWD mass per hectare of late-rotation forestland varied over a wider range than the county-level totals despite the median standard error being somewhat smaller at 46% (Figure 6). Although the magnitude of uncertainty in county-level estimates was generally large, some trends were evident from the maps. For example, counties on the northern edge of the natural range of loblolly pine tended to have lower CWD mass yields and higher uncertainty. A similar trend was noted for major metropolitan areas and areas surrounding large cities in the region: e.g. Atlanta, Georgia; Charlotte, North Carolina; Houston, Texas; and Jacksonville, Florida.

Discussion

Managed loblolly pine forests in the southern United States have been identified as a potential contributor to efforts that aim to increase carbon sequestration and storage (Johnsen *et al.*, 2001). Nearly half of the region's planted loblolly pine forests can be considered as "late-rotation" forests ranging in age between 15 and 45 years, such as the population studied here. As of 2006, coarse woody debris in late-rotation forests held an estimated 48.67 million Mg of dry wood necromass, the carbon equivalent of 24.33 million Mg. This matches 1.5% of GHG emissions from energy consumed in the United States in 2006 using a CO_2 equivalent basis (U.S. Environmental Protection Agency, 2008). However, this carbon amount may be underestimated because every model including used CWD predictive model has its own predictive ability and application restrictions. This predicted carbon here has accumulated over decades and represents only late-rotation loblolly pine plantations. It does not include CWD remaining in stands from previous rotations or the CWD accumulated following catastrophic mortality events such as hurricanes, ice storms, fire, or insect outbreaks for model parameters do not account for such events (Wade, 1993; Amateis and Burkhart, 1996; Price *et al.*, 1998; Oswalt *et al.*, 2008). Carbon content of 50% CWD dry mass was assumed, based on previous studies that have found this to be a reasonable value (Philip Radtke, personal communication, February 1, 2008), and other work that has failed to show significant trends between carbon content and wood decay status (Page-Dumroese and Jurgensen, 2006)

Forest plantations are subject to regular cycles of planting and harvesting, with silvicultural practices exerting significant effects on accumulations of CWD in individual stands (Duvall and Grigal, 1999; Ekbom *et al.*, 2006). Differences in management conditions, such as age, density, and extent of thinning directly affect region-wide CWD yields. Linking FIA field data with a stand-level CWD yield model enabled us to account for stand-level variables that affect CWD yield, while producing aggregated estimates of CWD for counties, states and the eleven-state region where loblolly pine is commercially grown.

Smith et al. (2004a) reported that the carbon content of CWD comprises about 8% of the total aboveground carbon in southeastern oak-pine forests. Using FIA data, our results showed that, in late-rotation plantations, CWD carbon ranged between 6% and 15% of the carbon stored in live stems. In pine plantations of Georgia and South Carolina, McMinn and Hardt (1996) estimated state-level CWD yield between 2.24 and 5.70 $Mg{\cdot}ha^{-1}$ by broad ownership classes. State FIA results showed that CWD yields ranged from 6.5 to 7.8 $Mg{\cdot}ha^{-1}$ in Virginia (Forest Inventory and Analysis, 2007). Applegate (2008) obtained estimates varying between 6.1 and 45.1 $Mg{\cdot}ha^{-1}$ with a mean of 19.5 $Mg{\cdot}ha^{-1}$ for pine forests in Virginia. Smith and Heath (2002) reported forest floor carbon values – which included litter and fine woody material but not CWD – in southern pines ranging from 1.4 to 21.9 $Mg{\cdot}ha^{-1}$. By comparison, we obtained statewide average values of CWD mass ranging from about 6.5 to 13.3 $Mg{\cdot}ha^{-1}$. Considering that these estimates included only late-rotation plantations, they seem consistent with previously-published work from field studies. In contrast, the results reported here were obtained at regional scales by aggregating stand-level CWD estimates from FIA Phase II inventory data and a stand-level regression model.

The sampling error approximated by a bootstrap method resulted in a 3.11% standard error for CWD yield on 48.67 million Mg of CWD in late-rotation southern loblolly pine plantations, corresponding to an error rate of about 21.7% for one million Mg. Forest Service sampling error targets for FIA timber-based attributes specify error rates of 5% or less for one billion cubic feet of growing stock, equivalent to a maximum error rate of 19% per one million Mg of growing stock (Gibson *et al.*, 1986; Forest Inventory and Analysis, 2009a). By comparison, CWD estimates from FIA Phase III data are expected to be subject to larger sampling errors, with analysts advised to be cautious of estimates derived on survey units having only small numbers of Phase III plots (Woodall and Monleon, 2008). While the standard errors estimated here appear to be larger than the sampling error targets for FIA timber attributes, they may be in line with expectations for standard errors of Phase III CWD indicators. The ability here to obtain state-by-state estimates for late-rotation thinned or unthinned loblolly pine plantations, despite uncertainties that exceed FIA Phase II error requirements, probably exceeds the capabilities of Phase III CWD inventory data. Additional work may be warranted as the collection of Phase III data grows over time to verify the accuracy of model-predicted results like those obtained here.

A source of error not accounted for here is the uncertainty of predictions generated from [1] due to the model's inability to make predictions with complete accuracy. When any regression model's predictions are subsequently used as inputs to other models or, as was done here, multiplied by area factors, and aggregated, the resulting estimates will have increased variance and may also be biased. Here, bias was presumably small because the aggregation procedure simply summed area-weighted predictions from [1], which amounts to a linear combination of the predictions (Kangas, 1997), and because an adjustment for predictions made on a logarithmic scale was used (Baskerville, 1972). In contrast, the standard deviation observed here among predictions of CWD yield on FIA Phase II plots was about one-half as large as the standard deviation reported by Applegate (2008) for CWD yield observations made directly on FIA Phase III-style plots in southern pine forests.

Because of its empirical basis, the regression model used to make CWD yield predictions should give unbiased predictions across a wide range of plantation conditions (Figure 2); however, it does not incorporate mechanistic principles that would make it suitable for prediction outside this range. The definition of late-rotation plantations here was chosen to match the range of conditions observed in the data set used for model development by Radtke et al. (2009). The regression model [1] may be susceptible to underestimation biases, especially at early ages, due to its failure to account for CWD that persisted from previous rotations, harvesting residues that may have persisted to the late-rotation stage, or non-planted trees such as competing hardwoods that may have died and contributed to the total CWD pool. While efforts were made to reduce the biases associated with CWD or residues that pre-date a current rotation, results reported here should be interpreted only with regard to those loblolly pine crop trees that were planted at the start of current rotations. This interpretation may be useful to agencies and organizations that wish to quantify the amount of carbon stored in CWD across the region directly attributable to management in loblolly pine plantations.

While the uncertainty of model-based predictions and its affect on subsequent aggregated estimates for counties and states was not directly accounted for, the model-based approach used here leveraged existing FIA Phase II data with information contained in an empirical model designed for this specific purpose. The approach aimed to provide estimates of CWD yields for assessing carbon in one important forest component pool at regional scales. Sample-based approaches include the work of Chojnacky and Schuler (2004) who obtained a standard error of 14%, directly from CWD field measurements for the CWD mass per hectare in a region spanning eastern states of Kentucky, North Carolina, Tennessee, and Virginia. Applegate (2008) observed a standard error for sample-based CWD estimates of 13% over a roughly 7,000 ha forestland area in the Fort A.P. Hill Military Installation in northeastern Virginia, across multiple forest cover types and structural conditions.

Softwood timber harvests are forecast to continue growing through 2040 in the South, with plantation management expected to increase in intensity as well (Prestemon and Abt, 2002). Under intensive management regimes, rotation lengths tend to be shorter and stands are more frequently subjected to human-induced disturbance, i.e. thinning and other intermediate treatments are prescribed more frequently. Over time, the carbon stored in CWD in southern loblolly pine plantations is unlikely to remain static. Ongoing inventory efforts like those of FIA Phase III will undoubtedly become increasingly useful for formulating regional estimates of CWD yield as they come online. Approaches that link field inventory data to model predictions like the one used here can provide additional information, fill in where data sets are incomplete, or serve as a means to validate or refine field estimates.

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Table 1. CWD mass totals and means per hectare at state and south-wide scales with standard errors and 95% confidence intervals.

	CWD mass total (10^6 Mg)				CWD mass mean (Mg·ha^{-1})			
State	Estimate	SE[†] (%)	95% CI		Estimate	SE[†] (%)	95% CI	
			Lower	Upper			Lower	Upper
Alabama	6.47	9.70	5.27	7.71	8.78	8.31	7.35	10.33
Arkansas	4.19	11.49	3.32	5.22	7.85	9.70	6.46	9.47
Florida	1.11	17.36	0.76	1.51	6.94	13.88	5.26	8.93
Georgia	6.69	8.97	5.57	7.9	7.07	7.88	6.04	8.23
Louisiana	4.27	13.09	3.29	5.45	9.08	11.71	7.16	11.29
Mississippi	5.65	7.85	4.86	6.57	6.46	6.38	5.70	7.34
North Carolina	8.69	10.09	6.99	10.49	13.31	8.07	11.31	15.49
South Carolina	6.15	8.78	5.15	7.24	8.51	7.31	7.40	9.80
Tennessee	0.63	31.92	0.28	1.08	10.78	25.22	6.08	16.57
Texas	2.45	13.97	1.84	3.14	6.45	12.24	5.03	8.08
Virginia	2.38	13.57	1.77	3.03	8.27	10.91	6.59	10.13
South	48.67	3.11	45.63	51.67	8.36	3.05	7.86	8.88

[†] Standard Error

Table 2. State ranking and summary statistics for plantation areas and management conditions including area thinned, age (A), density (N), and height of dominant and codominant trees (HD).

State	Plantation area (ha)		Area thinned (%)	FIA average[1]		
	Total[2]	Late-rotation[3]		A (yr)	N (trees·ha^{-1})	HD (m)
Alabama	2,069,546 (1)	736,350 (3)	39.61 (6)	21.7 (10)	664 (8)	18.79 (4)
Arkansas	959,073 (7)	533,404 (6)	54.37 (4)	24.8 (2)	676 (6)	17.69 (10)
Florida	262,631 (10)	159,893 (10)	40.44 (5)	22.3 (7)	652 (9)	18.01 (9)
Georgia	1,724,204 (3)	946,739 (1)	36.07 (7)	21.4 (11)	734 (4)	18.19 (7)
Louisiana	1,151,727 (5)	470,750 (7)	63.27 (1)	24.3 (4)	640 (10)	19.96 (1)
Mississippi	1,778,567 (2)	874,090 (2)	59.50 (2)	22.5 (6)	678 (5)	19.82 (2)
North Carolina	1,040,267 (6)	653,304 (5)	32.69 (8)	25.2 (1)	672 (7)	19.28 (3)
South Carolina	1,164,124 (4)	722,724 (4)	30.83 (9)	22.2 (8)	761 (3)	18.50 (6)
Tennessee	155,129 (11)	58,331 (11)	20.30 (11)	23.7 (5)	786 (2)	17.47 (11)
Texas	891,620 (8)	379,025 (8)	58.81 (3)	22.1 (9)	615 (11)	18.16 (8)
Virginia	677,327 (9)	287,524 (9)	30.75 (10)	24.5 (3)	938 (1)	18.68 (5)
South	11,874,215	5,822,134	44.06	22.9	701	18.78

[1] Averages weighted by forestland area for late-rotation plantations

[2] Loblolly pine plantation forestland regardless of stand treatment or age

[3] Thinned or unthinned stands between ages 15 and 45 years

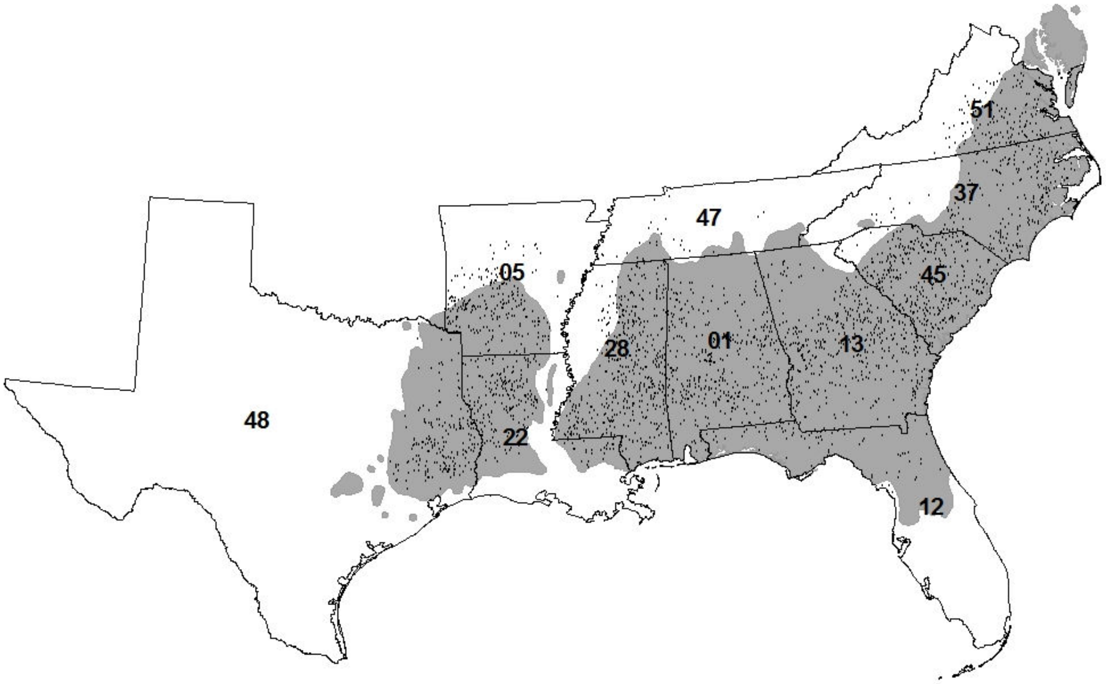

Figure 1. Approximate Forest Inventory and Analysis (FIA) plot locations for loblolly pine plantations and the natural range[†] of loblolly pine forests (shaded) in the southern United States. State codes – 01: Alabama, 05: Arkansas, 12: Florida, 13: Georgia, 22: Louisiana, 28: Mississippi, 37: North Carolina, 45: South Carolina, 47: Tennessee, 48: Texas, and 51: Virginia.

[†] Geographic distribution of loblolly pine is obtained from Little (1971).

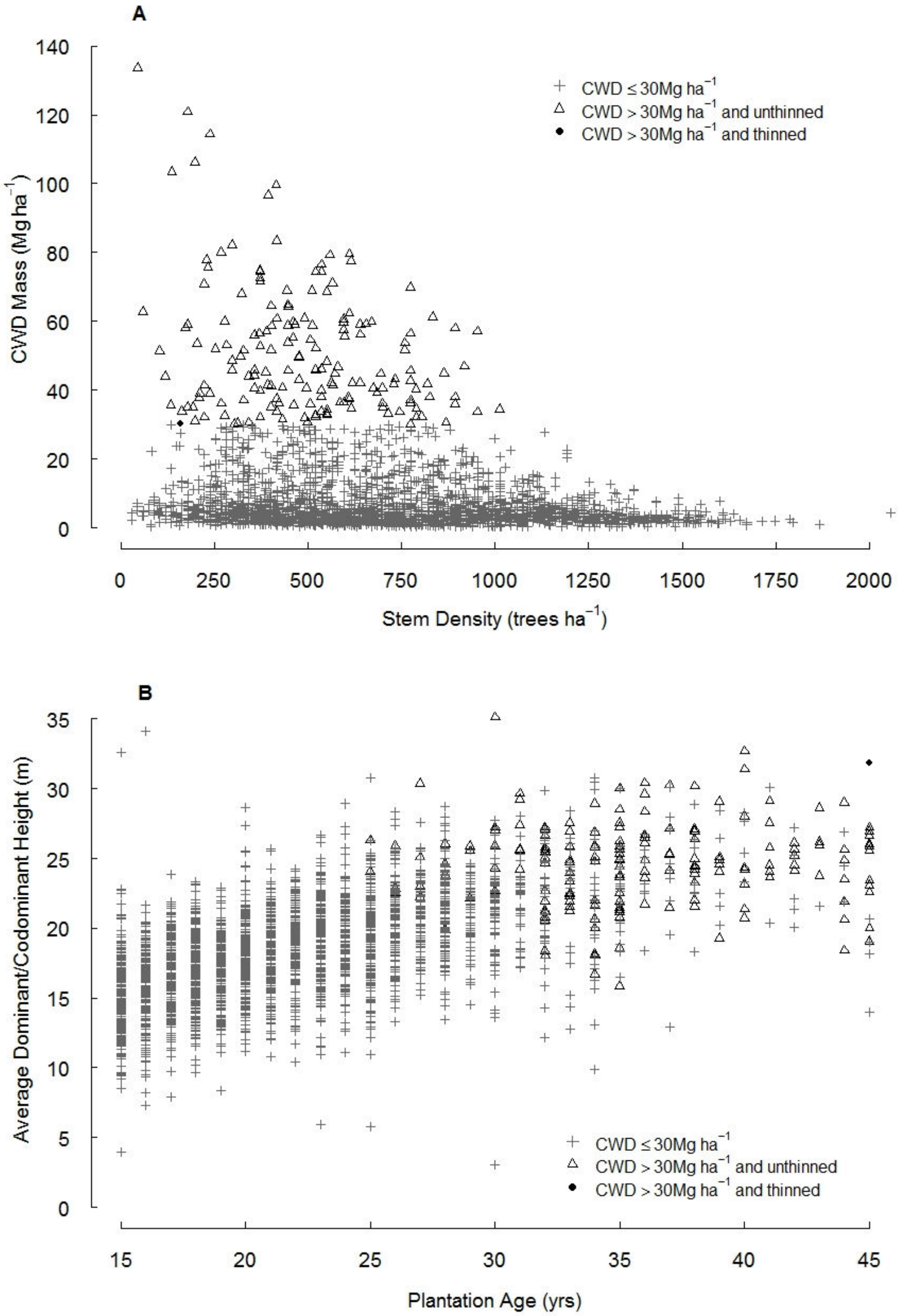

Figure 2. Pairwise distributions for stand-level predicted CWD from Eq. [1] and predictors including stem density, plantation age, and average dominant/codominant height. Seven observations having > 2000 trees·ha^{-1} are omitted from the truncated scatterplot (A).

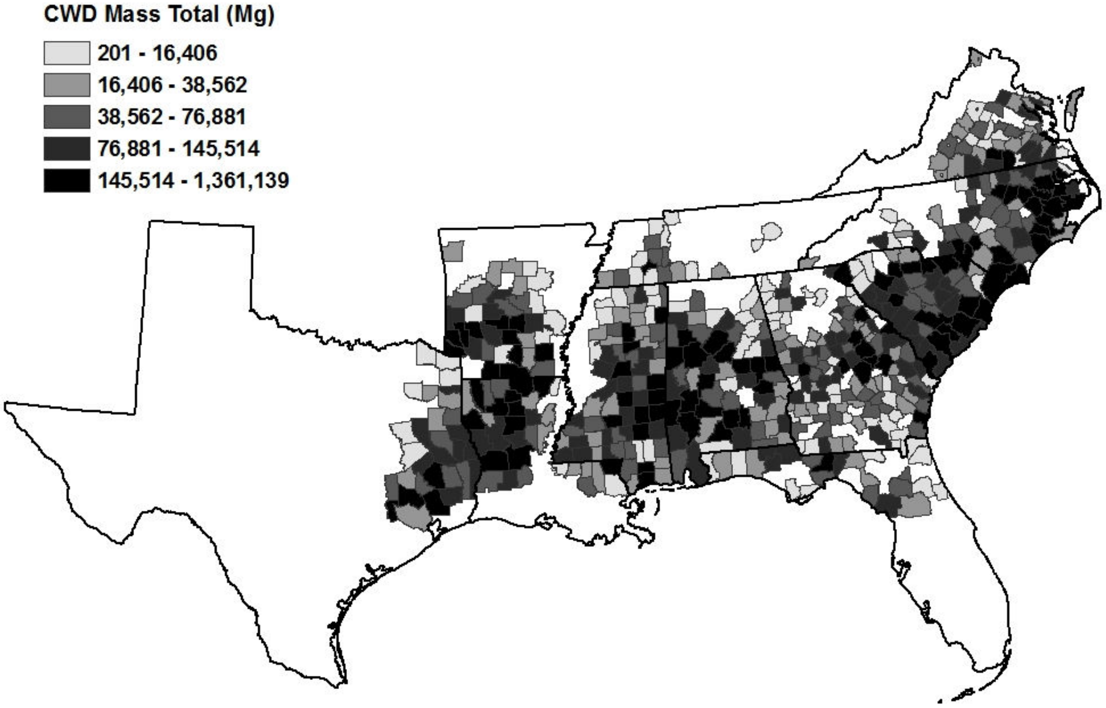

Figure 3. Total mass for county-level CWD (Mg) using the 20th, 40th, 60th and 80th percentiles as cutoffs between map legend groups.

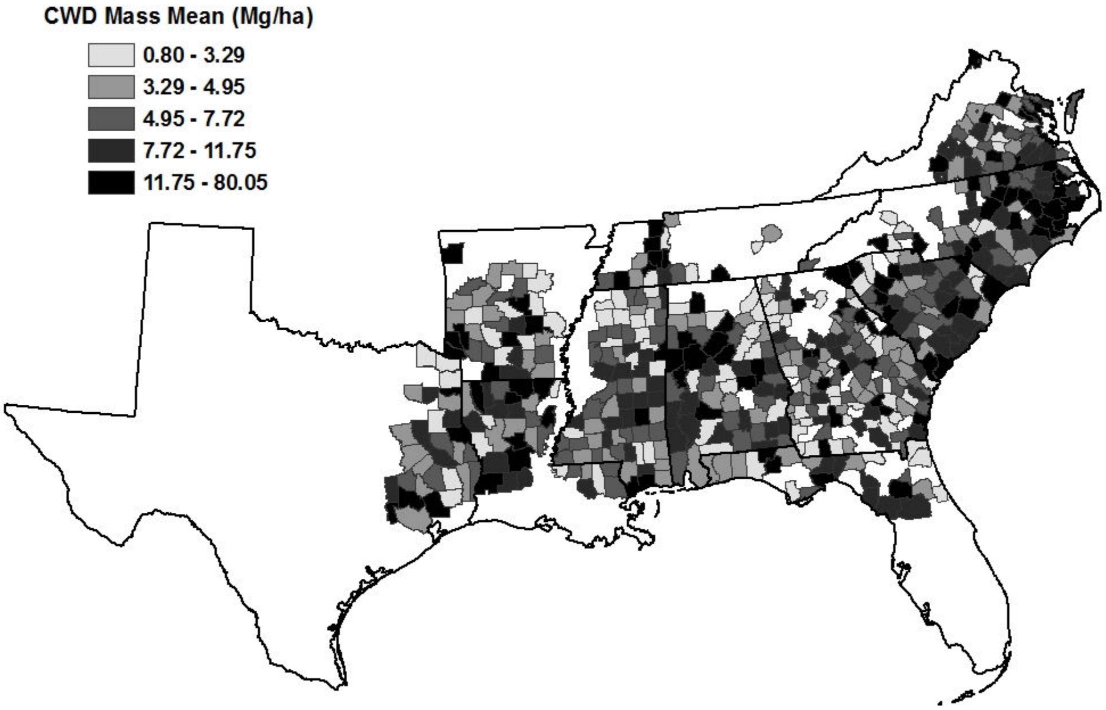

Figure 4. Mean mass for county-level CWD (Mg·ha^{-1}) using the 20th, 40th, 60th and 80th percentiles as cutoffs between map legend groups.

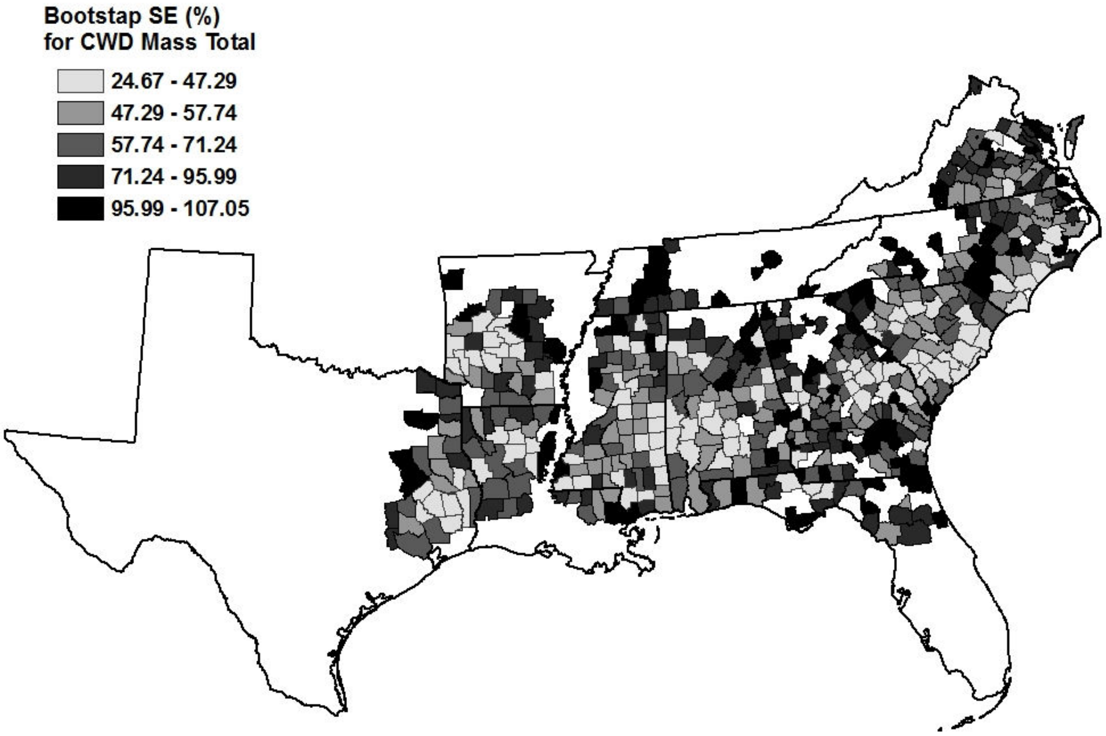

Figure 5. Bootstrap estimates of standard error (%) for county-level total CWD mass using the 20th, 40th, 60th and 80th percentiles as cutoffs between map legend groups.

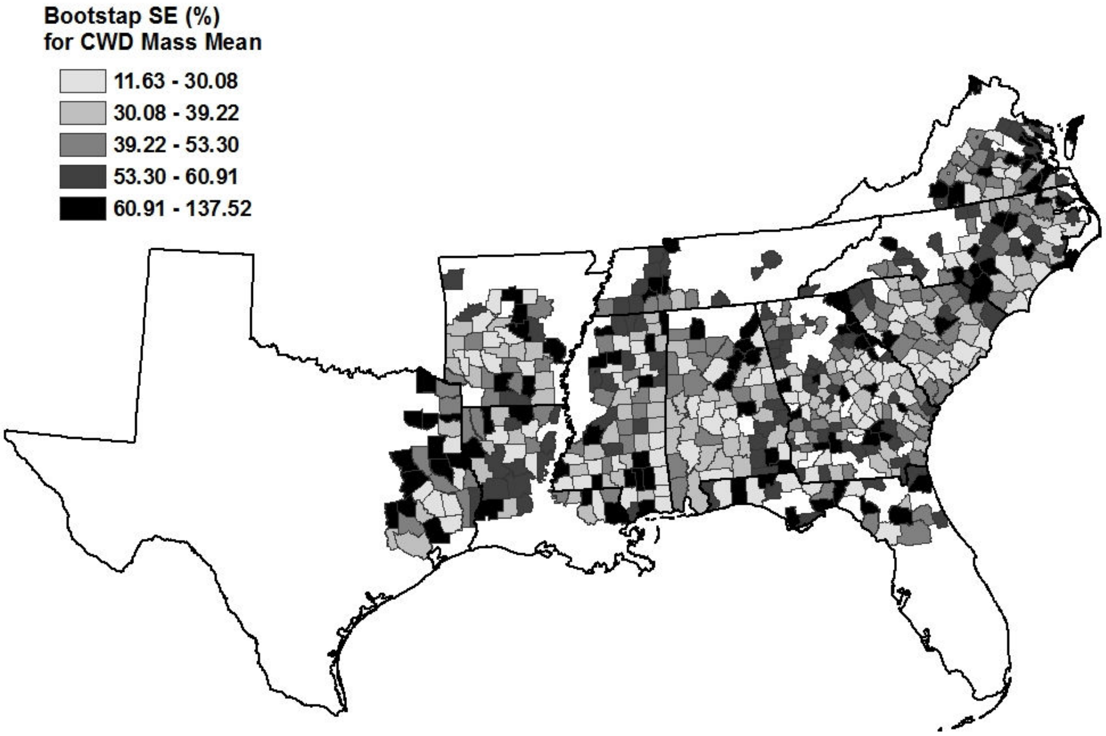

Figure 6. Bootstrap estimates of standard error (%) for county-level CWD mass per hectare using the 20th, 40th, 60th and 80th percentiles as cutoffs between map legend groups.

Effects of Forest Management on In-woods and Harvested Carbon Pools in Southern Loblolly Pine Plantations over a 50-year Projection Period

Abstract

Accounting for forest components in carbon accounting systems may be insufficient when substantial amounts of sequestered carbon are harvested and converted to wood products in use and in landfill. The potential of forest offset – in-woods aboveground carbon storage, carbon stored in harvested wood, and energy offset by burning harvested wood – from loblolly pine plantations was evaluated for GHG mitigation over a half-century period. The in-woods carbon in well-managed loblolly pine plantations across the South totaled 341 million metric tons. This represents 20% of total energy-consumed GHG emission on a CO_2 equivalent basis in the United States in 2006. Present-day carbon storage in southern pine plantations averaged 30.54 $Mg \cdot ha^{-1}$ (± 2.54%) for in-woods carbon. Annual wood production was 62.1 and 45.9 million green metric tons from pulpwood and sawtimber yield, respectively, with roughly one-fourth of the green weight being carbon. The carbon storage in wood products increased steadily over the half-century projection and showed no sign of leveling off, while the storage in plantations was found to remain constant or increase slightly over time. An additional 11 million metric tons of harvested carbon was used for energy per year on average, equivalent to 25% of annual forest-products-industry renewable energy use in U.S.A. Intensified application of fertilizers and herbicide and genetic improvement showed the potential to increase total storage in in-wood and harvested carbon pools as much as 30%, and energy offset up to 40%. Reducing management intensity greatly increased in-woods carbon storage potential, but eliminated the wood-products carbon sink.

Keywords: *Pinus taeda*; wood products; forest inventory; FIA

Introduction

Forest ecosystems in the United States sequester 140-300 million metric tons (Mg) of carbon per year, or between 18% and 39% of the equivalent CO_2 emissions from the Nation's coal-fired power plants (Pacala *et al.*, 2001; Heath and Smith, 2004; U.S. Environmental Protection Agency, 2007b). Despite scientists' knowledge that U.S. forests are an important terrestrial carbon sink, challenges remain in estimating the magnitudes of carbon storage attributed to forests in different geographic regions and in quantifying the magnitudes of fluxes for various forest carbon pools (Houghton *et al.*, 1999; Schimel *et al.*, 2000; Pacala *et al.*, 2001; Janssens *et al.*, 2003). One challenge involves incorporating uncertainty into estimates, so that decision-makers can plan in accordance with the quality of information in-hand (Gong, 1998; McKenney *et al.*, 2004). Another challenge is to account for carbon sequestered in wood removed from forests as wood and paper products that may persist for long periods of time (Skog and Nicholson, 1998; Perez-Garcia *et al.*, 2005). Such information is generally not a standard component in forest carbon estimates (Heath *et al.*, 2003); however, both concerns are essential in making decision or plans for managed forest ecosystems, including the loblolly pine (*Pinus taeda* L.) plantations extensive throughout the southern United States.

Carbon stored above ground in loblolly pine plantations includes both merchantable and non-merchantable trees and vegetation, along with dead wood and plant detritus (Smith *et al.*, 2004a). Regarding "long-lived" aboveground carbon pools, i.e. those in which carbon remains sequestered for decades or more, separate accounting is often made for live trees and coarse woody debris (CWD) based on the differing biological and ecological processes acting on each. Live trees sequester carbon on temporal scales of several decades, corresponding to rotation lengths. Carbon in CWD may persist in forests for years to decades depending on the relative rates of accumulation and decomposition (Duvall and Grigal, 1999; Vanderwel *et al.*, 2008; Radtke *et al.*, 2009). While aboveground carbon stored in live trees can be reliably assessed and projected over time and space, accumulations of CWD are considerably variable across landscapes and depend significantly on disturbance and management (Duvall and Grigal, 1999; Fridman and Walheim, 2000; Campbell *et al.*, 2008).

In evaluating the potential of managed forest ecosystems such as loblolly pine plantations in mitigating atmospheric GHG accumulations from the burning of fossil fuels, accounting for carbon stored in live trees and CWD is insufficient because substantial amounts of sequestered carbon are harvested and converted to end-use wood products, e.g. building materials, furniture, and paper products, or used as a fuel source to displace GHG emission from fossil fuels (Birdsey and Heath, 1995; Smith *et al.*, 2006). Although harvested wood is not a part of in-woods carbon pools, the linkages between management activities, forest carbon sequestration, and the timing and amount of wood harvested are inextricable. Wood products may persist longer than plantation rotation lengths, and the amount of carbon remaining in wood products – products in use and landfills – contributes significantly to carbon sequestration over time (Skog and Nicholson, 1998). Moreover, the magnitudes and rates of carbon remaining in wood products depend on the timing, intensity, and extent of harvesting activities, which affects what products the harvested wood is allocated to and life spans of wood in these products. On the other hand, wood processing at mills, e.g. drying, peeling, slicing, and sawing, uses energy from burning wood residues and pulping liquors that reduces some need for using fossil fuels. Such energy sources currently supply 1.5% of the total energy consumption in the U.S.A. (Perlack *et al.*, 2005). Compared to the combustion of fossil fuels, bioenergy from harvested wood is relatively carbon-neutral and can be renewable (Schiermeier *et al.*, 2008). Reliable accounts of long-term carbon mitigation potential from these managed ecosystems should not fail to take harvested carbon into account (Smith *et al.*, 2006). As demand for wood products grows, so too will plantation management intensity. Both factors will likely impact the amount of atmospheric carbon sequestered in southern U.S. forests and the wood products derived from them. Effective policy-making, planning, and management will require good information to ensure that these factors are accurately accounted for in optimizing carbon sequestration that can be supported by southern U.S. forests (Wear and Greis, 2002).

Plantation management in the U.S. South is expected to increase in intensity in order to provide more raw materials to meet rising societal demands for wood resources (Prestemon and Abt, 2002). Loblolly pine plantations comprise 9.7 million hectares of southern U.S. timberland, roughly 65% of the southern plantation area, and their area is projected to increase by 67 percent in the next thirty years (Prestemon and Abt, 2002; Wear and Greis, 2002; Smith *et al.*, 2004c). Through woody and herbaceous vegetation control and fertilization, site characteristics are being actively managed to enhance productivity (Allen, 2001). Intensive site preparation, including bedding, disking, subsoiling, ripping, or combinations of these treatments, can efficiently reduce competition from non-commercial hardwood species (Morris and Lowery, 1988). In addition, herbicide application can improve seedling establishment and early growth (Nilsson and Allen, 2003). Fertilization has become an important silvicultural tool in treating nutrient-deficient midrotation stands for increasing volume growth (Fox *et al.*, 2007). Planting genetically-improved growing stock has become a standard management tool to increase growth efficiency, with gains in volume growth averaging 10 to 30% over unimproved planting stock at harvest (Li *et al.*, 1999; McKeand *et al.*, 2003). Tree breeding and other efforts to improve genetic properties of plantation growing stock are increasingly producing commercially available families and genotypes for increased volume production in loblolly pine (McKeand *et al.*, 2003; Allen *et al.*, 2005; McKeand *et al.*, 2006). Intensive management operations appear to have potential for sequestering greater carbon, and projections of management scenarios will provide an insight on dynamics of in-woods and products-based carbon pools.

Recently, national-scale inventory-based carbon assessments have been augmented to account for carbon stored in aboveground forest pools, as well as the carbon stored in wood products (Skog and Nicholson, 1998; Heath *et al.*, 2003; Jenkins *et al.*, 2003; Smith *et al.*, 2003). To date, such assessments have not directly considered the resolution, intensity, nor timing of management activities prescribed at forest stand scales. Because management is typically carried out on the scale of forest stands, carbon accounting at the same scale will allow for tracking of the full range of management and harvesting activities (Harmon, 2001). In addition, stand-level accounting can be scaled up with increasing certainty, while downscaling of national-scale estimates generally leads to greater uncertainty (Freese, 1967; Smith *et al.*, 2004a). Here, predictions will be made at the resolution of individual forest stands for greatest flexibility in prescribing management conditions. Results will be aggregated to state and regional scales to make broader geographic assessments, presumably with a relatively high degree of precision (Smith *et al.*, 2004a). The resulting analyses should serve the information needs of individuals ranging from those who develop policies for climate change mitigation, to those who set long-term regional goals for carbon sequestration, to those who aim to increase the total carbon stored in the wood grown on and products harvested from their forest lands.

The goal of this research was to assess impacts of forest management on carbon storage in loblolly pine plantations across the southern United States over the next half-century. Of specific interest here are the in-wood carbon pools of aboveground live tree and CWD, and pools of carbon in wood products produced from southern forests. To preserve information related to stand-level management activities, extensive field-plot inventory data were coupled with stand-level prediction models to reduce uncertainty in estimates and facilitate aggregation across different spatial and temporal scales. Four specific objectives were pursued as a part of the overall goal:

Objective 1 Estimate the amount of carbon stored aboveground in live trees and CWD at scales ranging from individual stands to the entire southern United States.

Objective 2 Predict the annual production of harvested wood under operational management over a 50-year span, distinguishing between wood harvested for use in solid wood and paper products, and accounting for trends related to management intensity;

Objective 3 Project in-woods carbon pools and carbon disposition in harvested wood over a 50-year time span, linking inventory-based data and management activities to existing models of growth and yield and accounting for the lifespan of wood products;

Objective 4 Evaluate long-term effects of intensive management of loblolly pine in the U.S. South, including competing vegetation control, fertilization, and planting of genetically improved growing stock, on carbon sequestration and storage.

Materials and Methods

Data

The primary data source used in addressing the study objectives is the database of forest inventory records available online from the USDA Forest Service Forest Inventory and Analysis (FIA) program (Forest Inventory and Analysis, 2009a). The FIA data used here are composed of two-phase sample data collected using double-sampling for stratification (Smith, 2002; Reams *et al.*, 2005). Phase I data begin with the interpretation and classification of remote-sensing imagery. Strata weights are estimated for each remote-sensing class, and areas of interest, such as the areal extent of loblolly plantations, can be estimated by aggregation based on strata weights. Phase II field plots are established on subsets of Phase I strata to provide field observations of forest conditions and conventional timber-based measurements on trees larger than 2.54 cm diameter at breast height (DBH). The spatial sampling intensity of FIA field plots is one plot per 2,430 hectares, and each field plot comprises a cluster of four 7-m fixed-radius subplots, occupying a 0.067-ha area (Bechtold and Scott, 2005). Within each subplot is nested a 2-m radius microplot where detailed measurements of small trees (< 2.54 cm DBH) are made.

Phase II inventory data obtained, from 2005 – 2007 survey data for loblolly pine plantations of 11 southern states (Figure 7, Table 3), were used as the source of information for stand information, including plot datasets, plot-condition datasets, tree datasets, seedling datasets, and site-tree datasets (Forest Inventory and Analysis, 2009a). Plot datasets bridged Phase I data and plot-condition datasets to estimate forestland areas represented by each plot given its growing condition. Plot datasets provided plot geographic coordinates, remeasurement period (yr), a unique plot identification code and previous plot conditions if any remeaurement occurred. Field observations from plot condition datasets included plot conditional classes, condition status codes, condition proportions, subplot proportions, stand origin codes (natural stands or plantations), stand origin species, stand ages, treatment codes, year of treatment, and year of inventory. Conventional timber-based variables from tree datasets measured in subplots included tree status codes (live or removed), species, DBH, height, and live/removed cubic-foot volumes. Site-tree data included site index relevant measurements, i.e. height and age of dominant or codominant sample trees. Seedling data measured in microplots provided information on planting density.

The FIA data were screened to identify conditions consistent with “well-managed” loblolly pine plantations such as those used in the development of the FASTLOB growth-and-yield model developed by the Forest Modeling Research Cooperative at Virginia Tech (Amateis and Burkhart, 2009). Only those plantations having $\leqq$ 20% of the stand basal area comprised of hardwood species and those having ages between 0 and 50 years were defined as “well-managed” and subsequently included in the analyses. These conditions were consistent with the data used to develop FASTLOB and its computer implementation (Ralph Amateis, personal communication, March 1, 2010). Among 12.4 million hectares of planted loblolly pine forest, a set of 5,480 FIA inventory plots matched the screening conditions and the total area was 11.2 million hectares, including 3,139 plots on which the screened condition was observed on the entire plot, and 2,341 on which the screened condition was observed on a portion of the plot.

Stand-level growth-and-yield model

The FASTLOB model was developed to reflect management activities common to loblolly pine plantations established from the late 1950s to early 1990s (Amateis and Burkhart, 2009). FASTLOB uses site index (base age 25 years), age, stem density, amount of competing vegetation, thinning operations, fertilization, and other stand characteristics to project merchantable yields (pulpwood and sawtimber) and in-woods biomass by component, including stem and bark, branches and bark, foliage, and CWD, at different ages. Not only projections but also predictive values for initial growing stock can be obtained while inputs are established. Stand-level equations that comprise the nucleus of FASTLOB project dominant height, survival and basal area, and serve as a baseline thinned and unthinned model for stands. In addition, model inputs including information of latitude and longitude provide more precise locale-specific predictions if data are available. FASTLOB is presently used in ongoing forest management across the private sector of the South.

Quantify current forest carbon pools

Coupled with FIA stand attributes, FASTLOB was used to initialize current stand-level forest carbon pools, but an indication of how close the estimate from FIA is to the population parameter was not readily available through applying FIA area expansion factors to scaling up stand-level estimates to state and southwide levels (Scott *et al.*, 2005). “Forest carbon pools” in this study refer to the carbon content (one-half the mass of oven-dry biomass) in aboveground live trees and CWD, including standing snages and downed-woody material. Variances of in-woods carbon estimates were used to characterize the uncertainty of current forest carbon pools.

Bootstrap variance estimation and its corresponding Monte Carlo approximation were used to compute the estimate of in-woods carbon mass (live trees and CWD) at various regional scales (Booth and Sarkar, 1998). Because the probability density function of the population distribution was unknown, a nonparametric approach was applied to assess various regional-level carbon quantities. In the application of bootstrap sampling, predictive values of current in-woods carbon mass from FASTLOB initialization, weighted with representative areas for each FIA plot, were treated as a substitute for the population of in-woods carbon. Then, from these 5,480 observations (the number of FIA plots in the dataset), bootstrap samples of size 5,480 were selected with replacement from the FIA dataset. An estimate of in-woods carbon was obtained from each bootstrap sample at state and southwide levels. Two thousand bootstrap samples from the data were generated in total (Booth and Sarkar, 1998). Standard errors and the 2.5th and 97.5th percentiles of the confidence interval for the in-woods carbon were then approximated from the bootstrap sample distributions.

Assumptions of baseline management

Management conditions considered here included the area and density of planting, timing and intensity of thinnings, ages to harvest (rotation ages), and silvicultural activities associated with high-intensity management. Final (clearcut) harvests are simply referred to as "harvest" in this study, in contrast to wood harvested by thinning, which is referred to simply as "thinning." Maximum-likelihood was used in analyzing FIA data to estimate parameters for management-related inputs including planting densities, levels of residual stems per unit area, and ages for thinning. Log-normal distributions were fitted to planting density and residual stem density. A gamma distribution was fitted to approximate the distribution of thinning ages for subsequent simulations. Empirical cumulative distribution functions (ECDFs) and Quantile-Quantile (Q-Q) plots were used to evaluate quality of fit for empirical frequencies with those fitted to density functions.

Distribution functions were fitted to 2005 – 2007 measured plot attributes from FIA to simulate inputs for simulations to be consistent with real-world conditions of planting density, timing, and intensity of thinning (Figure 8, Figure 9, Figure 10). Mean and median planting densities of 1,473 and 1,349 trees·ha^{-1}, respectively, coincided with planting spacings typical of southern U.S. pine plantations and a lognormal distribution function fitted to FIA data (Figure 8). No relationship existed between age of thinning and site index. Therefore, age of thinning from FIA records was fitted to a gamma distribution function (Figure 9). Post-thinning residual densities were simulated by a lognormal distribution (Figure 10). All three of these distribution functions represented the general shape and scale of the FIA data for planting density, thinning age and residual density, although some lack-of-fit was noted, especially in the upper tails of these right-skewed distributions.

Rotation length, the plantation age at final harvest, was needed to schedule operations on individual stands; however, rotation length was only directly observed on a small number (n = 22) of the FIA phase II field plots – namely those that had been visited at two different times and were harvested between visits. In these data an inverse relationship between site index and rotation length was noted (Figure 11A). Their mean rotation length was 27.5 years (s = 6.1), over plantations that averaged 18.50 m in site index (s = 2.18). Although the relationship between rotation length and site index was relatively weak, a trend describing it (Figure 11A) was used to predict rotation length for the full set of FIA phase II plots where rotation lengths had not been observed. Predicted rotation lengths by plantation area averaged 27.5 years using this approach, with 80% of plantation area having rotation lengths between 23 and 32 years (Figure 11B). Dividing the total area of plantations by the mean predicted rotation length indicated an annual harvest area over time of 406,000 ha, which was roughly consistent with published report of 524,000 ha planted in loblolly and shortleaf pines in the southern U.S. in 1998 – including those subjected to all levels of management intensity (Moulton and Hernandez, 2000; Smith *et al.*, 2004c).

Simulation of silvicultural operations

Loblolly pine plantations were assumed to be managed primarily for timber benefits over the 50-year simulation. With regard to management objectives, plantations were categorized into two populations throughout the commercial range of species, those that would be thinned at some point during a rotation, and those that would remain unthinned up to the point of their final harvest. An area of 288,623 ha was set as the target for the area of thinnings to be simulated each year, based on the estimated annual area of thinning in FIA plantation area. The same area was targeted for final-harvest operations in previously-thinned stands each year so that the area of thinned plantations would remain constant over time. The area to be harvested annually from never-thinned stands was set at 117,377 ha as an initial target value, so that the area harvested from thinned and never-thinned plantations would target a total of 406,000 ha per year, as was determined in the previous section.

In simulation of area harvested annually from either thinned or unthinned stands, it was necessary to assign the annual area harvested to various plantation ages. Much as growth and yield share an inherent relationship the plantation area harvested in various age classes over time has an cumulative effect on the age distribution of plantation growing stock (Clutter *et al.*, 1983). To reflect this relationship, the mathematical derivative of plantation area with respect to age across the South was used in assigning an age distribution to the area annually harvested. To implement this method, plantation area was first expressed as a function of stand age to match the empirical conditions characterized from the FIA database.

Graphs of plantation area by age for thinned and unthinned stands showed distinct trends of declining area beginning around age 22 for thinned stands, and age 16 for those that were never thinned (Figure 12). These values were used to establish the minimum ages for final harvesting, i.e. the minimum rotation lengths, in thinned and unthinned plantations, respectively Then the first derivatives of area with respect to age were calculated to represent suitable functions of harvest area (i.e. change in plantation area) by plantation ages. These first derivatives of area harvested from thinned and unthinned stands were defined by functions, Eq. [1] and Eq. [2], respectively:

$$y = c_1 \times \left(1307x^{-2} - 133100x^{-3} + 3606000x^{-4} - 28876000x^{-5}\right) \times \exp\left(15.83 - 1307x^{-1} + 66550x^{-2} - 1202000x^{-3} + 7219000x^{-4}\right) \quad [1]$$

$$y = c_2 \times 0.13 \times \exp\left(15.16 - 0.13x\right) \quad [2]$$

where

x = stand age (yrs)

y_x = total area harvested at age x

c_1 and c_2 are refined factors through simulations

To focus on changes in plantation area that were due to removals by harvesting, only the declining portions of the age class by area distributions were considered (Figure 12). Thus, in accord with the FIA data it was assumed that final harvesting for thinned stands took place no sooner than 22 years after planting in loblolly pine plantations, and no sooner than 16 years for unthinned stands.

All thinnings were simulated based on a thinning intensity of 20% removals by row thinning and an additional ≧5% reduction in stem density removed by thinning from below. Following thinning, a minimum of 6 years was required in any particular stand before final harvest was allowed in order to capture the volume growth response to the thinning treatment. Timings and total area of plantation thinnings were specified by the gamma-model-specified distribution of stand ages at thinning, along with the target for total area to be thinned each year across the South. End-of-rotation harvest timing and area also targeted an age-distribution and total area. A time period for harvesting, site preparation and subsequent planting was assumed to be one year; therefore, artificial regeneration was simulated to follow an end-of-rotation harvest with a one-year fallow period.

Simulation annual operations

Forest management regimes span decades for a rotation, and individual stands experience all stages of the forest management cycle including final harvest, site preparation, regeneration, and thinning. Concerning stable production of timber harvests from year to year, total southern loblolly pine plantations were treated as a single entity and management activities were manipulated through coordinating all stands. Final harvests were assumed to be operated on 406,000 ha annually, i.e. 288,623 ha from previously-thinned stands and 117,377 ha from never-thinned stands. Regarding changes in plantation area on rotation ages, Eq. [1], Eq. [2], and rotation ages modified from FIA data (input rotation ages) were programmed into simulations of area harvested annually. Intermediate simulation results were used to refine the two constants c_1 and c_2 in Eqs. [1] and [2], respectively, along with the specified target area for annual harvesting in unthinned plantations. The sequence of steps performed in the simulation algorithm follows (Figure 13): (1) if stand age is equal to its predicted rotation age or greater, then this stand becomes one candidate to be harvested; (2) with regard to the size of candidates' representative area, candidates with large areas have top priority to be harvested; (3) select candidates from the pool of candidate stands to meet requests from each age-class area of Eq. [1] or Eq. [2]; (4) if total area from Step 3 meets the target harvest area, then stop; (5) otherwise, more candidate stands harvested are needed. In this step, number of overdue years of predicted rotation age is used instead as the criterion for choice of candidate stands to be harvested. Select candidates from more overdue years to meet target harvest area; (6) means of simulated rotation ages and areas harvested by year are evaluated whether simulation underperforms or not; (7) if underperformance occurs, refine c_1 in Eq. [1] or c_2 in Eq. [2]; (8) re-run steps 1-7 for the next 50-year-simulation iteration until simulation output is in good shape. After final harvest and a one-year fallow period for site preparation, all stands were established and their planting densities followed the lognormal-model-specified distribution.

Assignment of stands to be treated by thinning, or remain unthinned during the lengths of their rotations was made using a Bernoulli distribution with values 1 for thinning, and 0 for no thinning. The probability that a stand would be thinned (*p*) was defined by the total area harvested from thinned stands divided by total harvest area across the South from the previous year in the simulation. As previously noted, the area to be treated by thinnings annually was set at 288,623 ha and its age structure was defined by Eq.[1]. This simulation required four component inputs including target area, Eq. [1], input rotation ages, and the gamma-model-specified distribution of stand ages at thinning. The steps of the algorithm procedure follow (Figure 14): (1) if stand age is equal to its gamma-specified age or greater, then this stand becomes one candidate to be thinned; (2) candidates have top priority to be thinned if their representative area are large; (3) select candidate stands to meet demands of future harvest areas from Eq. [1] coupled with predicted rotation ages; (4) if total area from Step 3 meets target thinned area, then stop; (5) otherwise, select more candidate stands to meet the target area. Number of overdue years of thinned age serves as the criterion for choice of candidate stands to be thinned. From large overdue years, select candidate stands to meet target thinned area.

Harvested wood production over time

Projections of future production of timber products (i.e. pulpwood and sawtimber) were made under the baseline management scenario described above, which was determined from FIA data. Simulated variables including areas harvested either from thinned or unthinned stands, thinned areas, rotation ages, and ages for thinning were linked to FASTLOB to generate timber products estimates. Pulpwood was defined as 15.24 cm (6 in) DBH and larger and minimum diameter top was 10.16 cm (4 in) outside bark; and sawtimber was defined as 22.86 cm (9 in)

DBH and larger to a minimum 17.78 cm (7 in) top diameter outside bark using the International 1/4-inch log rule. Green weights outside bark for both types of timber products were predicted for comparison to regional analyses that express production on the basis of weight (Bullock and Burkhart, 2003). For validation purposes, primary-mill survey results from 2006-2008 were obtained from FIA timber product output (TPO) reports of pulpwood and sawtimber production from roundwood (e.g. Cooper and Becker, 2009; Johnson *et al.*, 2010).

To assess the potential role of wood products in mitigating GHG emission from fossil fuel, i.e. carbon pools and energy offset, the method for calculating harvested carbon by Smith et al. (2006) was used. The amount of carbon in wood products each year was estimated, including products in use and products in landfill, through 2056, beginning with wood harvested in 2006. Carbon remained in harvested wood products was expressed as metric tons per hectare ($Mg{\cdot}ha^{-1}$) even though the disposition of carbon over time for such wood products are not directly linked to forest area. With regard to renewable energy consumption from wood residues and pulping liquors generated by the forest products industry, the amount of emitted carbon by year was estimated. Year-to-year changes in stocks of carbon sequestered in the wood-products pool was estimated to evaluate whether this pool is a carbon sink, balance, or source.

The carbon content in harvested wood was estimated using green weight of pulpwood and sawtimber production from FASTLOB output and moisture content (MC) of sapwood 110% (Glass and Zelinka, 2010). Disposition of carbon in harvested wood products for products in use, products in landfill, and energy offset was estimated as follows: (1) $Ovendry\ weight = Green\ weight \big/ \left(MC + 1 \right)$; 50% of this is carbon mass; (2) allocate sawtimber and pulpwood to primary wood products (e.g. lumber, plywood, panels, and paper) according to region and category in Table D6 of Smith et al. (2006); (3) compute carbon amount of primary products remaining in use or in landfill each year based on Tables 8 and 9 of Smith et al. (2006), respectively; (4) estimate amount of carbon associated with energy recapture using Table D7 of Smith et al. (2006) (See appendix A for these tables).

In-woods carbon over time

To evaluate long-term effects of baseline management on sequestering carbon and maintaining in-woods carbon, FASTLOB was used to project biomass of aboveground live trees and mass of CWD in a 50-year timeframe since 2006. Rate of change of sequestering carbon was computed to assess whether the managed forest was a carbon-balanced system or not. FASTLOB has embedded prediction equations that estimate biomass for various components (Baldwin *et al.*, 1997; Landsberg and Waring, 1997; Radtke *et al.*, 2009). Carbon mass was assumed to be 50% of biomass (Smith *et al.*, 2003).

Intensive management scenarios

With regard to an increase in management intensity in the southern plantations, two management intensity scenarios were developed to estimate potential loblolly pine growth and yield and the corresponding effects of management on carbon storage. The two management scenarios included (1) scenario 1: intensive site preparation, herbicide application, and mid-rotation fertilization; and (2) scenario 2: the management regime from scenario 1 plus planting of genetically improved growing stock. The term "genetically improved" here assumes that growing stock came from third- or fourth-generation seed orchards which have not previously been deployed in the South (McKeand *et al.*, 2003).

The intensive management regimes 1 and 2 were used according to the embedded functionality of the FASTLOB modeling system. For completeness, an overview of the FASTLOB implementation for intensive management is given here. Growth responses to intensive silviculture in FASTLOB are added to baseline-management predictions. According to research that showed growth responses to intensive site preparation and herbicide application varying from site to site, the effect of competing vegetation control on growth and yield was modeled in FASTLOB by increasing site index by 0 to 1.5 m (Siry *et al.*, 2001; Nilsson and Allen, 2003). A uniform distribution was used to simulate random site index increases within this range for each stand. In accord with common mid-rotation fertilizer applications of 28 P $\text{kg}\cdot\text{ha}^{-1}$ and either 224 or 196 N $\text{kg}\cdot\text{ha}^{-1}$, the amount of N fertilizer applied in a given stand was set to follow a Bernoulli distribution with p (224 N $\text{kg}\cdot\text{ha}^{-1}$) = 0.58, and $1 - p$ (196 N $\text{kg}\cdot\text{ha}^{-1}$) = 0.42 (Albaugh *et al.*, 2007). For unthinned stands, the timing of fertilization was assumed to take place between ages 13 to 20 and no harvesting within six years of fertilizing; for thinned stands fertilization was performed after thinning. Timing assumptions for fertilization were primarily based on published studies varying management intensities that Siry et al. (2001) assumed fertilization at age 15 years for medium intensity and 5-to-10 years for high intensity; Allen et al. (2005) assumed age 17 years for medium intensity and 5-to-21 years for high intensity; Liechty and Fristoe (2010) used ages 17-to-22 years for timing of mid-rotation fertilization. Genetically improved stock was assumed to increase volume by 10 to 20% at harvest ages and this increase corresponded to a 1.5- to 3-m site index gain (McKeand *et al.*, 2006). Site index gains due to planting of genetically improved seedlings were simulated by generating a uniform random variate on the interval [1.5, 3.0] for each stand.

Results

Estimates for current carbon pools

In well-managed loblolly pine forestland across the South, the estimate of in-woods carbon mass total exceeded 340 million Mg (1 Mg = 1 metric ton or approximately 1.1 U.S. tons)

(Table 4). The mean of area-weighted averaged carbon was 30.54 Mg·ha^{-1}. State-by-state in-woods carbon totals varied from 3.3 to 53.7 million Mg, and 21.30 to 35.51 Mg·ha^{-1} for carbon means per hectare by accounting for forestland area (Table 4). Carbon total stocks in Tennessee and Florida were significantly less than those in the other nine states, largely due to their comparatively small plantation areas. Aside from the effects due to its small plantation areas, Tennessee had relatively low carbon stocks of 21.30 Mg·ha^{-1}, in part because of its comparatively low average basal area (Table 3). In general, states with the lowest average plantation ages had the lowest yields per hectare, while those with the highest plantation ages had higher yields (Table 3, Table 4). The percentages of aboveground live trees and CWD, contributing to the in-woods aboveground carbon pool, were about 93% and 7%, respectively (Table 5, Table 6).

Bootstrap results

Sampling distributions for in-wood carbon quantities (i.e. carbon total and carbon per hectare) in loblolly pine plantations across the South appeared to be consistent with a normal distribution, with the bootstrap-simulated means being approximately equal to estimates from FASTLOB (Figure 15, Figure 16). The simulated results for standard errors and the 2.5th and 97.5th percentiles of distributions were given in Table 4 , Table 5 , and Table 6. Bootstrap confidence intervals for southwide carbon spanned ±2.80% for total carbon mass and ±2.54% for carbon per hectare (Mg·ha^{-1}) in the in-woods pool, respectively. Variances in live-tree carbon were ±2.77% and ±2.44% for carbon total and per hectare, respectively, and those of CWD carbon quantities were ±7.38% and ±7.30%.

State-level uncertainties for estimates of carbon quantities were assessed using the same set of bootstrap samples (Table 4, Table 5, Table 6). Compared to southwide estimates, state-by-state estimates were relatively imprecise. Uncertainty in the in-woods estimates was primarily contributed by variability from live-tree pools. Despite the larger dispersion of CWD pools across states, because of their smaller size, CWD pools contributed less to overall in-woods variablity. Tennessee and Florida had greater variance of carbon estimates, mainly because of the relatively small numbers of FIA field plots in loblolly pine plantations in those states. Therefore, their standard errors of estimated totals and means for in-woods carbon were relatively large compared to other states' estimates. Excepting Tennessee and Florida, 95% bootstrap confidence intervals for states' carbon means in well-managed plantation forestland did not exceed ±15% of the estimated values.

Age-class simulations of area

The target area for annual harvesting from unthinned stands was set to 112,583 ha following test simulations used to determine whether this value was consistent with the constant c_2 in Eq. [2]. Hypothetical distributions of harvest area by age classes (Figure 17), were multiplied by constants $c_1 = -2.48$ in Eq. [1] and $c_2 = -0.65$ in Eq. [2], which ensured consistency between target harvest areas, Eqs. [1] and [2], and the predicted distribution of rotation ages. The derivative functions or harvest area by age classes reflect the assumed restriction of final harvesting in thinned plantations to those $\geqq$22 years of age and unthinned plantations $\geqq$16 years. In addition, these hypothetical distributions, especially the harvest curve for thinned stands [1], agreed with the predicted distribution of rotation ages (Figure 11B, Figure 17).

In plotting the area of simulated thinning and final harvest operations in each year of the simulation (Figure 18A), two periods, each spanning about 10-years, reflected relatively low projected areas of thinning (2015 – 2025) and final harvest (2025 – 2035) activity. These periods corresponded to a decade of relatively low establishment of loblolly pine plantations across the South in the 1990s, which is reflected in the relatively low area of 5 to 15 year old plantations in the initial age-class distribution (Figure 19A). At the end of the 50-year simulation, the same pattern was not evident in the age-class structure of loblolly pine plantation area across the South (Figure 19B).

Simulated results of year-by-year areas operated by thinning and harvesting, and their corresponding mean ages for operations were plotted in Figure 18. The annual area of final harvest averaged 400,000 ha over the 50-year simulation, including 290,000 ha (± 9,600) harvested from thinned stands and 110,000 ha (± 3,300) from unthinned stands. Rotation lengths in the simulations ranged between 26 and 33 years. Accounting for the occurrence of projected thinnings, simulated rotation ages of thinned stands averaged about one year more than those of unthinned stands, at 28.2 and 27.4 years, respectively. The annual area of thinning operations averaged 280,147 ha with a standard deviation of 27,000 ha over 50 years, with an average age of thinning = 18.0 years (s = 0.7 yrs).

Projected timber production

An example of the effect the simulated thinning regime had on stand-level volume and biomass accretion over the 50-year projection period can be compared with that of a stand not subjected to thinning (Figure 20). In both thinned and unthinned simulated stands, all aboveground volume and CWD was set to zero prior to the artificial regeneration of the stands. As is typical of most models that project growth and yield after thinning in plantations, volume was immediately reduced at the time of thinning, and then allowed to re-accumulate over time until final harvest. In the years immediately following thinning, standing volume growth rates exceeded the rates realized before thinning for a time; however, volume production at final harvest was lower in thinned stands than their unthinned counterparts. The period of no apparent volume or biomass that occurs between rotations is a minor artifact of the way volume accretion is estimated in FASTLOB. In particular, the youngest age at which any volume outputs are generated is five years after planting.

Timber production southwide for each year was computed as an aggregate of all stand-level projections. Results showed that through carrying out thinning operations, stands supplied one-fourth timber production annually including pulpwood and sawtimber, and final harvest three fourths, drawn from Figure 21. Further, thinnings primarily produced pulpwood; and final harvests produced pulpwood and sawtimber. Annual total pulpwood yield was 62.1 million green metric tons, ranging from about 49 to 76 million green metric tons, 38% from thinning and 62% from final harvest. However, total sawtimber production of 36 – 60 million green metric tons was almost 100% made up by final harvests. Mean projected annual pulpwood production was nearly equivalent to 2006 – 2008 TPO reported pulpwood production. For sawtimber the projected mean was about 35% lower than the TPO value (Figure 21).

Carbon pools and fluxes

Figure 22. showed the effects of annual thinning and final harvesting activities on reductions of carbon from the in-woods pool. Intra-annual increases in the trend represented net growth through the growing season, while intra-annual decreases represented removals. Timing of removals was arbitrarily set to follow the annual growth each year, without detailed consideration of the timing of growth and removals within any given year. Considering both additions and losses of carbon in the wood-products pool, which includes products in use and in landfills, harvested wood products created a sink of 6 to 9 million metric tons of carbon per year (Figure 23). Compared to the landfill pool, fluxes of sequestered carbon in the products-in-use fluctuated more from year to year, especially in pulpwood products because of their relatively

short lifetimes. For a long run, landfills added more carbon in the accounting system with reference to annual positive carbon fluxes.

Effects of various management intensities

Regarding increasing demands of wood products, intensive management might provide opportunities for GHG mitigation. With the intensive approaches, the amount of carbon stored in all individual pools was substantially increased. Overall, applying fertilizers and herbicide, and deploying genetically improved growing stock increased 15% of carbon stocks, respectively (Figure 24). However, the increased magnitudes varied among pools. The more-intensive scenario (scenario 1) produced carbon gains 20% in sawtimber-in-use, and 10% in pulpwood-in-use, landfill, and in-woods pools, respectively. For the most-intensive scenario (scenario 2), sawtimber-in-use had a 40% increase; pulpwood-in-use and landfill had a 25% increase, respectively; and in-woods had a 35% increase in carbon stocks by comparing to the baseline scenario. For both intensive-management scenarios, carbon stocks in sawtimber-in-use grew much faster than the other pools, primarily due to gains in volume growth that increased long-lifetime sawtimber production (Figure 25).

Beginning with applying more intensive silvicultural approaches in 2006 and following each year, southwide-level timber yield responded to such applications with a time lag at least four years (Figure 25). Use of fertilizers and herbicide enabled substantial increase in pulpwood yields from 2013 and sawtimber yields from 2010. Genetic improvements increased pulpwood yields from 2021 and sawtimber yields from 2027. As expected, with increasing yield, annual energy recapture from wood products increased 20% and 40% for the more- and most-intensive scenarios, respectively, compared to the burning wood products of 11 million metric tons of carbon per year from the base scenario (Figure 26).

Discussion and Conclusions

Regional forest carbon storage in loblolly pine plantations was modeled as an aggregate of stand-level estimates based on FIA data and FASTLOB, which served as a baseline for assessing the potential of managed extensive forests to increase carbon storage. As of 2006, aboveground carbon pools held an estimated 341 million metric tons of carbon, an amount equivalent to 20% of GHG emissions from energy consumed in the United States in 2006 (U.S. Environmental Protection Agency, 2008). This estimate corresponded to an average of 31 Mg of carbon accumulated on each hectare of planted loblolly pine across the South. Sources other than planted loblolly pines are excluded from these estimates. Live trees comprised 93 % of the projected aboveground carbon, with the remaining 7% stored in CWD. Smith et al. (2004b) reported that carbon content in aboveground woody pools ranged between 43 and 60 $Mg \cdot ha^{-1}$ in southern loblolly-shortleaf pine forests. Their comparatively high estimates included some 45% natural forests, by area, compared to only plantations considered here (Forest Inventory and Analysis, 2009a). Presumably, the relatively low management intensity in natural forests allows for greater accumulations of in-woods carbon than what is accomplished in well-managed plantations. Smith et al. (2004b) also reported that CWD comprised 12% of in-woods carbon, an amount higher than was found here. This difference can also be attributed to differences in management intensity between their study data set and the one used here. Compared to the 11.17 million hectares of “well-managed” loblolly pine forests studied here, the FIA loblolly-shortleaf forest type comprised 25.2 million hectares of forestland (Forest Inventory and Analysis, 2009a).

Uncertainties for baseline carbon assessments were approximated by a bootstrap procedure that showed error rates of 1.40% for total carbon across the South and 1.27% for carbon mass per hectare. The relatively small sampling error rates confirm that in-woods carbon estimates from FIA survey data can be highly precise (Figure 15, Figure 16). Smith and Heath (2001) reported an error rate of 6.5% for carbon mass stored in aboveground softwoods of maple-beech-birch forests for area of 10^5-10^7 ha, based on growing stock used by FIA (Smith *et al.*, 2003; Smith *et al.*, 2004a). Bootstrap error rates for loblolly pine plantation area estimates from the same FIA data used here (details not shown) verified that the FIA-mandated maximum sampling error rate of 1.91% for one million hectares of forestland was not exceeded (Forest Inventory and Analysis, 2009a). These results support the widely-held understanding of bootstrap sampling as a state of the art method for quantifies uncertainty in complex statistical analyses such as the regional carbon estimates generated here.

Rotation lengths varied between 26 and 33 years for stands projected over the course of the baseline simulation, based on the targets established by the weak relationship between site index and rotation length noted in FIA data, and also accounting for target harvest levels, thinning, and the modeled age-distributions of thinning and harvesting operations over the region. Rotation lengths were generally consistent with optimal ages to harvest based on financial returns or experts' insight that final harvests occur between ages 25 and 35 years (Siry, 2002; Huang and Kronrad, 2006; Carino, 2009). Year-to-year simulated averaged ages of thinning between 17 and 20 years agreed with pulpwood harvest ages in southern pine plantations from 2000 through 2010 (Fox *et al.*, 2004). In addition, the dip in projected annual areas for thinnings and final harvests reflected past conditions. According to Conner and Hartsell (2002), industry ownership decreased throughout the South between 1989 and 1999, to the point where the removals of growing stock in 1999 exceeded the year's annual growth. Since then the area of southern pines planted has increased, in part because of conversion of some nonforested land area to pine plantations (Conner and Hartsell, 2002). The projected trends here reflect both the decrease in growing stock prior to 1999 and the subsequent increase reported by Conner and Hartsell (2002).

FIA initial area conditions most strongly influenced projection results during the first 30-years of the 50-year simulation period. Beyond 30 years, the assumptions embedded into the simulation, notably those assumptions related to areas managed over time, exerted stronger influence on projection results. This can be seen in the dip observed in the FIA age-class distribution (Figure 18, Figure 21) that affects areas projected to be available for thinning and final harvest, along with timber production, particularly sawtimber yields, through 2035. After 2035 projected timber production and areas harvested or thinned became relatively stable over time, presumably the result of the repeated application of modeling assumptions that fail to replicate variations that would occur under real-world conditions. In addition, the simulation assumed the area of plantation forestry will remain constant across the South for 50 years and that age distributions of growing stock and harvested wood will remain stable over time. Trends in demographics, land uses, timber supply-and-demand relationships, and timber price are all known to affect timber resources, but were deemed to be outside the scope of this study (Adams *et al.*, 2003). The simulation methods developed here could be improved upon by accounting for future dynamics of number of planted hectares, financial returns, and individual ownerships and their associated management objectives.

Projected sawtimber yields here were lower than reported TPO values by about 35%. In contrast pulpwood projections matched TPO reported values almost exactly. Sawtimber output in TPO reports are derived from the loblolly-shortleaf pine forest type, which includes natural and planted pine forests with all levels of management intensity. Management goals for such forests may be considerably different than what are defined here as “well-managed” loblolly pine plantations. For example, goals may include management for aesthetics, wildlife habitat, and recreational uses for a portion of the stand's lifetime, with sawtimber harvesting taking place once economic returns become a motivating factor (Guldin, 2004). On the other hand the fact that pulpwood production results here strongly agree with TPO pulpwood production implies that loblolly pine plantations are a major source of softwood raw material for pulpwood production in the South. Challenges remain for comparing broad-scale market results such as TPO to management-oriented projections like the one conducted here.

Based on this 50-year-projection method, long-term effects of thinning and final harvest on future carbon stock in the products-in-use and landfills can be extended through 100 years or more to address the climate change issue (Miner, 2006). Projected results showed that removals in the five decades total approximately 25.7 million metric tons of carbon per year, while maintaining the region's plantation resources with a net carbon increase in growing stock over time; the harvested wood product preserves carbon with a positive flux of 6-9 million metric tons per year; an average of 11 million metric tons per year of carbon is burned for energy, equivalent to 25% of annual forest-products-industry renewable energy use in U.S.A. (Perlack *et al.*, 2005).

It has been argued that forests managed under natural conditions will store more carbon than those managed for timber production, even when carbon stored in products are accounted for (Harmon *et al.*, 1990). For example, after a 50-year unmanaged period, all planted loblolly pine forests had quadratic mean breast height diameter of 15.5 cm, and averaged in-woods carbon mass of 115 $\text{Mg}\cdot\text{ha}^{-1}$, varying from 18 to 251 $\text{Mg}\cdot\text{ha}^{-1}$ (Figure 27A). Managed systems appear to store less carbon than their natural counterparts by means of projection (e.g. 75.3 $\text{Mg}\cdot\text{ha}^{-1}$ for the management regime and 115 $\text{Mg}\cdot\text{ha}^{-1}$ for the natural regime). Given enough time, however, carbon flux of old forests would theoretically approach zero for the rate of change of carbon accumulations (i.e. second derivative) is negative (Figure 27B). Such phenomenon in old forests is analogous to a carbon balance in planted forests between carbon captured by photosynthesis and carbon removed by thinning and final harvest. Further, wood products offer a potential advantage over manufactured materials for locking up sequestered carbon. For example, a simple sawed wood product requires 44% less energy consumption than steel, 93% less than aluminum, 60-80% less than concrete, or 77-83% less than plastic (Petersen and Solberg, 2005; Jansson *et al.*, 2010). Managing forests to supply wood products may provide low-cost opportunities for GHG mitigation. Therefore, proper carbon mitigation policy should be a compromise between managing forests and preserving forests.

Increased demand for wood products often results in landowners adopting more intensive forest management practices (Prestemon and Abt, 2002). Management scenarios showed that through intensified application of fertilizers and herbicide and genetic improvement, improved plantation productivity increases not only the production potential of forests but also in-wood/harvested carbon stock up to 30%. However, fertilizers and herbicide require additional energy to produce and apply, and some of the applied fertilizers and herbicide is inevitable lost as GHG such as N_2O (Sathre *et al.*, 2010). Such potential for lowering the GHG benefit is not accounted in management scenarios explored here.

In total, the carbon stored aboveground in loblolly pine plantations and wood harvested from them, including that used for energy production, has considerable potential to offset GHG emissions from fossil fuels. To better assess roles of such forest offset, GHG offset payments to landowners are necessary to model future market adjustments (Cairns and Lasserre, 2004; Im *et al.*, 2007). Forestry-related policies implemented in efforts to mitigate GHG emissions or accomplish other public goals have the potential to affect landowners’ management of plantation lands (Pohjola and Valsta, 2007). Despite the lack of any direct linkage to proposed public policies here, the approach used here allows for flexibility and adaptability in changing assumptions or inputs when new data and information become available. The results of projections like those presented here provide potentially useful information for use in addressing questions about the role southern pine plantations can play in GHG mitigation and climate policy.

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Table 3. Summary of stand attributes (area-weighted mean) for FIA sampled field plots and their representative forestland area of loblolly pine plantations by southern states

State	Plots	Area (10^6 ha)	SI[†] (m)	Planting (seedlings·ha^{-1})	Age (yrs)	TPA (trees·ha^{-1})	BA[‡] (m^2·ha^{-1})	Thinning	
								Age	TPA
Alabama	976	1.95	20.0	1,040	14	867	13.8	19	425
Arkansas	406	0.85	17.0	1,127	18	788	15.8	24	413
Florida	116	0.24	19.7	1,095	16	912	14.9	-	-
Georgia	833	1.66	19.8	941	16	870	14.2	20	390
Louisiana	508	1.09	19.7	1,038	14	964	14.2	23	467
Mississippi	823	1.63	19.8	1,080	15	833	14.9	21	445
North Carolina	394	1.00	18.5	1,191	19	818	15.6	24	319
South Carolina	575	1.10	19.6	1,240	17	855	16.1	21	405
Tennessee	83	0.15	18.5	751	14	754	11.5	20	425
Texas	437	0.87	19.1	1,176	14	843	12.6	18	415
Virginia	329	0.63	18.5	1,038	19	813	15.4	24	334
South	5,480	11.17	19.4	1,067	16	855	14.7	21	410

[†] Site index at base age of 25 years

[‡] Basal area

Table 4. State-level and southwide in-woods carbon mass totals (10^6 Mg) and means (Mg·ha^{-1}): FIA estimates and bootstrap standard errors and 95% confidence intervals

	In-woods carbon total (10^6 Mg)				In-woods carbon mean (Mg·ha^{-1})			
State	Estimate[†]	SE[‡] (%)	95% CI		Estimate[†]	SE[‡] (%)	95% CI	
			2.5th	97.5th			2.5th	97.5th
Alabama	53.7	4.21	49.4	58.2	27.49	2.74	26.02	28.89
Arkansas	26.7	7.12	23.2	30.7	31.43	4.69	28.69	34.39
Florida	7.2	12.35	5.5	9.1	30.25	7.70	25.76	34.98
Georgia	49.4	4.50	45.1	53.8	29.83	2.86	28.19	31.55
Louisiana	31.2	6.89	27.1	35.4	28.58	5.33	25.67	31.59
Mississippi	52.5	4.52	47.9	57.2	32.11	2.90	30.28	33.91
North Carolina	35.4	6.73	30.7	40.3	35.51	4.36	32.48	38.53
South Carolina	38.5	5.58	34.4	42.8	34.97	3.42	32.66	37.20
Tennessee	3.3	18.15	2.2	4.5	21.30	12.94	15.84	26.69
Texas	21.4	6.78	18.6	24.2	24.52	4.66	22.43	26.86
Virginia	22.1	7.71	18.7	25.4	34.99	4.75	31.74	38.15
South	341.1	1.40	331.7	350.5	30.54	1.27	29.77	31.31

[†] Estimate based on FIA 2005 – 2007 data and FASTLOB yield predictions

[‡] Estimated standard error from bootstrap sampling

Table 5. State-level and southwide live-tree carbon mass totals (10^6 Mg) and means (Mg·ha^{-1}): FIA estimates and bootstrap standard errors and 95% confidence intervals

State	Live-tree carbon total (10^6 Mg)				Live-tree carbon mean (Mg·ha^{-1})			
	Estimate[†]	SE[‡] (%)	95% CI		Estimate[†]	SE[‡] (%)	95% CI	
			2.5th	97.5th			2.5th	97.5th
Alabama	50.5	4.19	46.5	54.7	25.85	2.71	24.46	27.17
Arkansas	24.6	6.88	21.4	28.0	28.96	4.36	26.56	31.50
Florida	6.8	12.36	5.2	8.6	28.62	7.70	24.33	33.08
Georgia	46.8	4.49	42.7	50.8	28.22	2.82	26.64	29.82
Louisiana	28.5	6.62	24.9	32.1	26.11	4.93	23.70	28.65
Mississippi	49.5	4.49	45.1	53.8	30.28	2.84	28.58	31.95
North Carolina	31.3	6.47	27.3	35.5	31.35	3.94	28.99	33.71
South Carolina	36.1	5.59	32.2	40.2	32.78	3.41	30.57	34.90
Tennessee	3.0	18.17	2.0	4.1	19.53	12.92	14.50	24.52
Texas	19.9	6.65	17.3	22.5	22.81	4.45	20.97	24.83
Virginia	19.7	7.51	16.8	22.6	31.28	4.42	28.57	33.91
South	316.4	1.35	308.1	324.7	28.32	1.22	27.63	29.00

[†] Estimate based on FIA 2005 – 2007 data and FASTLOB yield predictions

[‡] Estimated standard error from bootstrap sampling

Table 6. State-level and southwide CWD carbon mass totals (10^6 Mg) and means (Mg·ha^{-1}): FIA estimates and bootstrap standard errors and 95% confidence intervals

State	CWD carbon total (10^6 Mg)				CWD carbon mean (Mg·ha^{-1})			
	Estimate[†]	SE[‡] (%)	95% CI		Estimate[†]	SE[‡] (%)	95% CI	
			2.5th	97.5th			2.5th	97.5th
Alabama	3.2	8.59	2.7	3.8	1.65	8.01	1.39	1.91
Arkansas	2.1	15.16	1.6	2.8	2.47	13.99	1.87	3.20
Florida	0.4	15.94	0.3	0.5	1.63	12.86	1.24	2.06
Georgia	2.7	6.90	2.4	3.1	1.61	6.11	1.44	1.81
Louisiana	2.7	15.23	2.0	3.6	2.47	14.75	1.81	3.24
Mississippi	3.0	7.17	2.6	3.4	1.83	6.35	1.61	2.07
North Carolina	4.2	13.30	3.2	5.4	4.16	12.31	3.27	5.29
South Carolina	2.4	7.56	2.1	2.8	2.19	6.38	1.91	2.46
Tennessee	0.3	32.96	0.1	0.5	1.77	30.62	0.84	2.89
Texas	1.5	13.49	1.1	1.9	1.71	12.65	1.31	2.16
Virginia	2.4	14.69	1.8	3.1	3.71	13.36	2.83	4.77
South	24.7	3.69	23.0	26.5	2.21	3.65	2.06	2.38

[†] Estimate based on FIA 2005 – 2007 data and FASTLOB yield predictions

[‡] Estimated standard error from bootstrap sampling

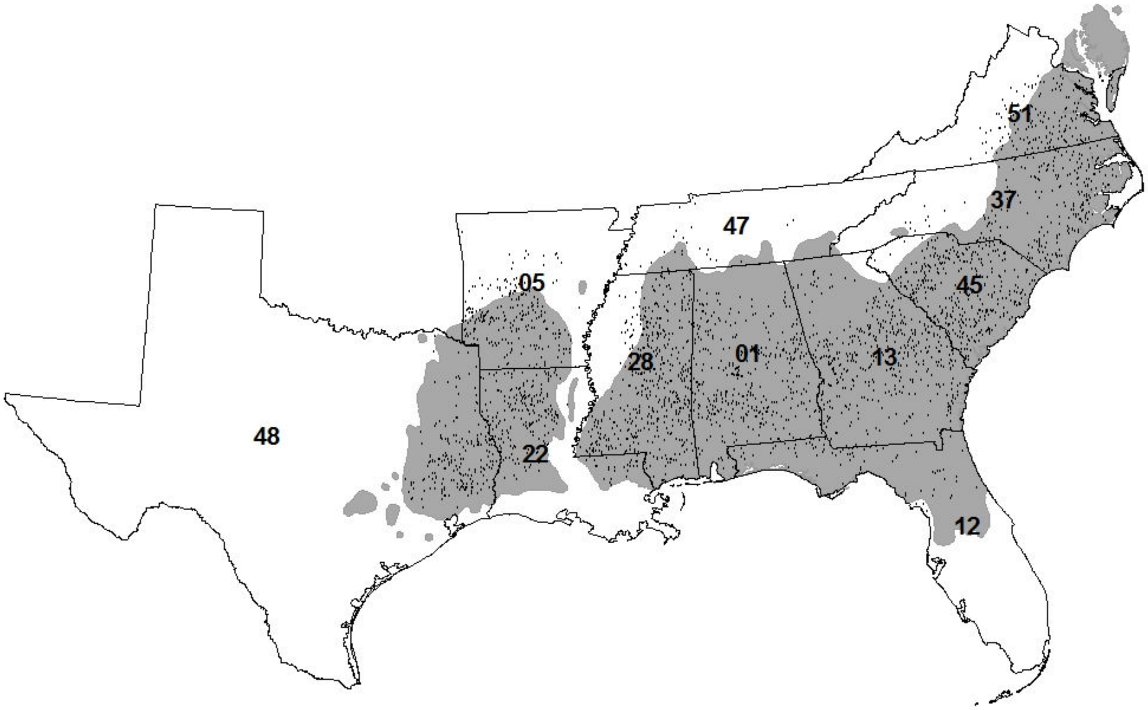

Figure 7. Approximate Forest Inventory and Analysis (FIA) plot locations for loblolly pine plantations and the natural range[†] of loblolly pine forests (shaded) in the southern United States. State codes – 01: Alabama, 05: Arkansas, 12: Florida, 13: Georgia, 22: Louisiana, 28: Mississippi, 37: North Carolina, 45: South Carolina, 47: Tennessee, 48: Texas, and 51: Virginia.

[†] Geographic distribution of loblolly pine is obtained from Little (1971).

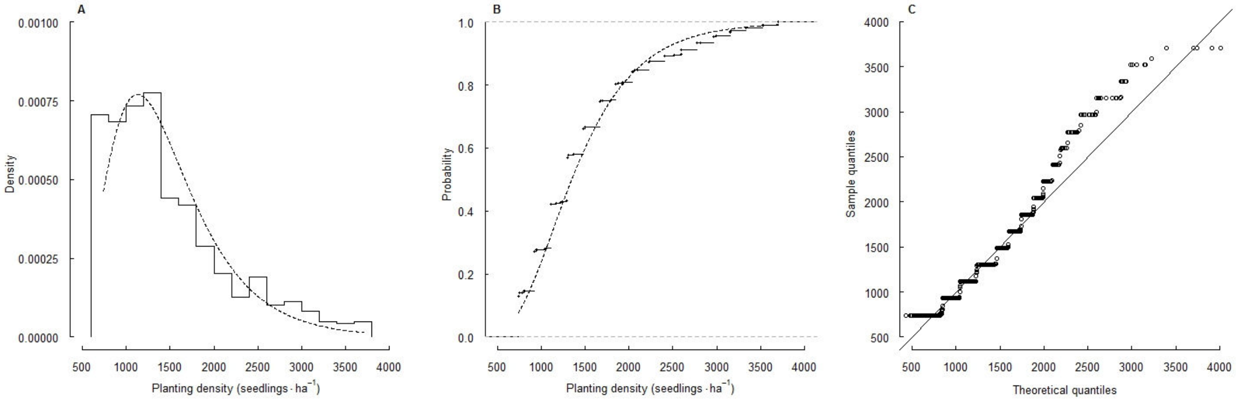

Figure 8. Fitted log-normal distribution of planting density ($\mu = 7.21$, $\sigma = 0.42$ while the variable at natural logarithm scale): (A) Histogram of observed data versus fundamental shape; (B) Empirical versus theoretical cumulative distribution functions (ECDF versus CDF) (C) Empirical quantiles versus theoretical quantiles from a log-normal distribution.

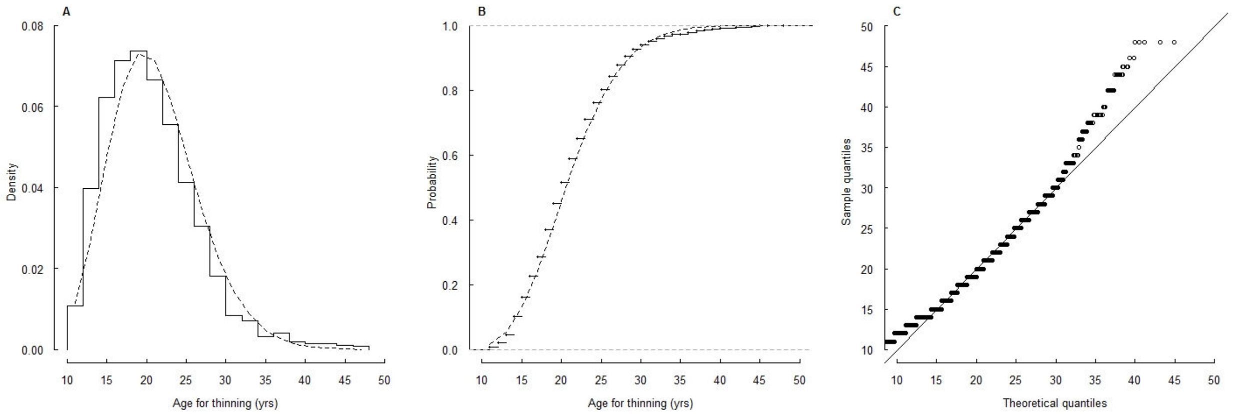

Figure 9. Fitted gamma distribution of age of thinning ($\alpha = 14.31$, $\lambda = 0.68$): (A) Histogram of observed data and fitted gamma density function; (B) ECDF versus CDF; (C) Empirical quantiles versus theoretical quantiles from a gamma distribution.

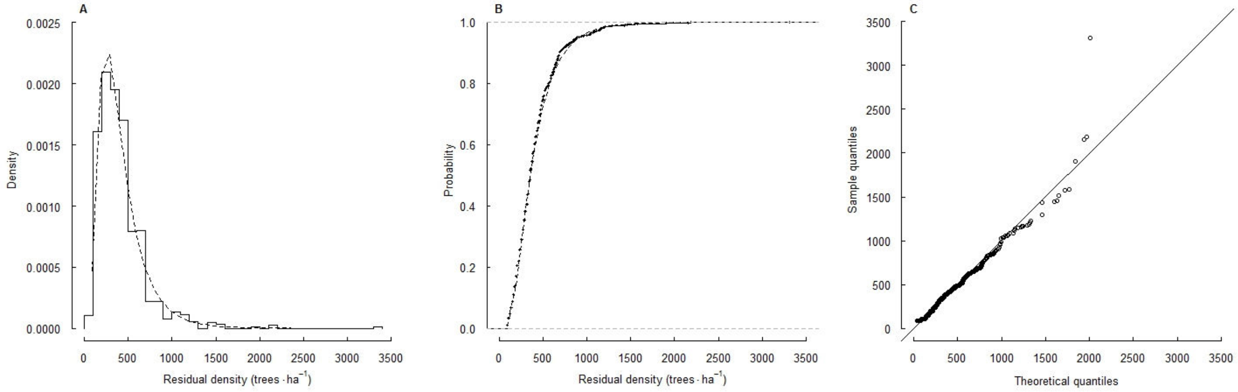

Figure 10. Fitted log-normal distribution of residual density after thinning ($\mu = 5.86$, $\sigma = 0.58$ while the variable at natural logarithm scale): (A) Histogram of observed data and fitted lognormal function; (B) ECDF versus CDF (C) Empirical quantiles versus theoretical quantiles from a log-normal distribution.

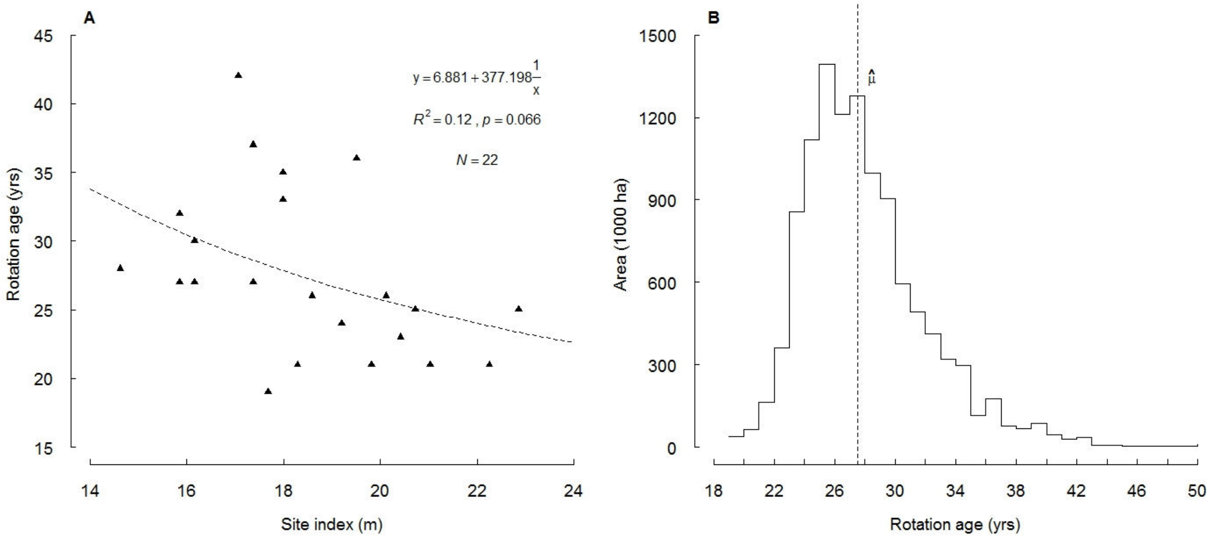

Figure 11. Distribution of rotation ages, accounting for site index at base age 25: (A) The relationship between FIA observed rotation ages and site index; (B) Predicted rotation ages for all stands across the South with a mean $\hat{\mu} = 27.5$.

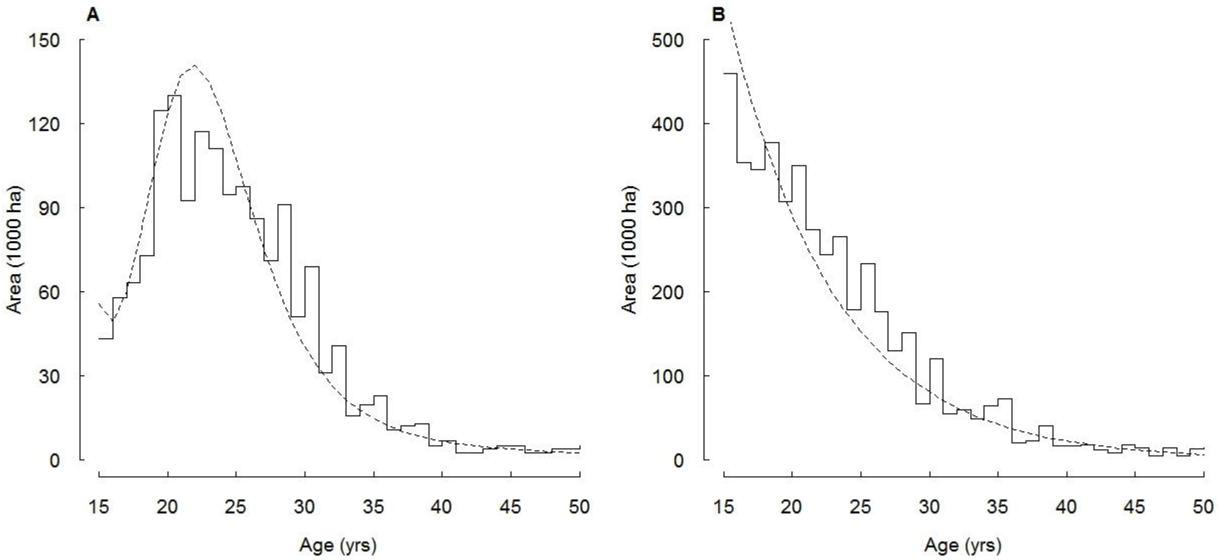

Figure 12. Quality of fit for distributions of planted area by age classes throughout the South (A) Stands with evidence of thinning which age class at 22 yrs has largest fitted area; (B) Stands without thinning observed which age class at 16 yrs has largest fitted area.

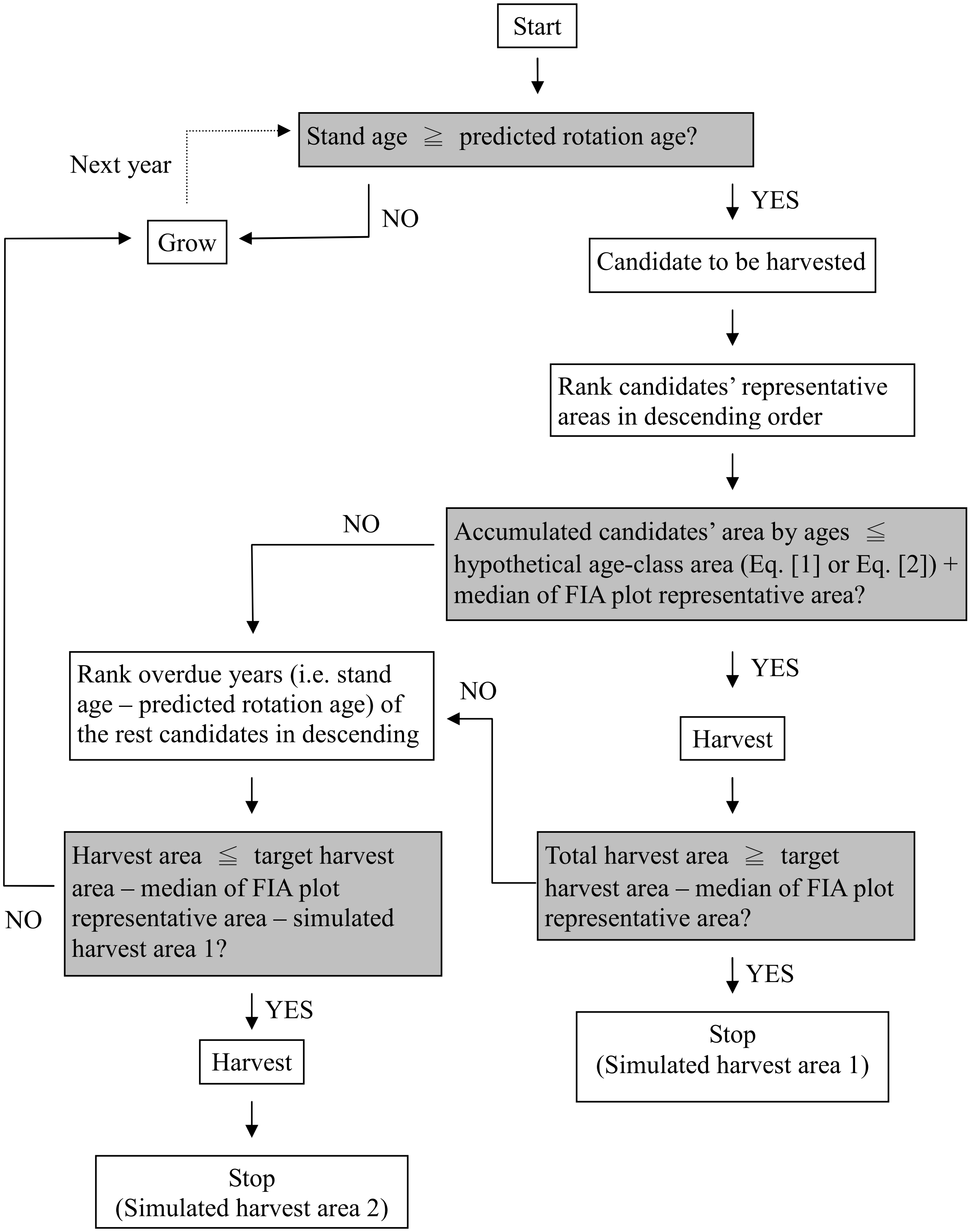

Figure 13. Rules used to select FIA plots for harvesting from thinned [1] and never-thinned [2] plantations.

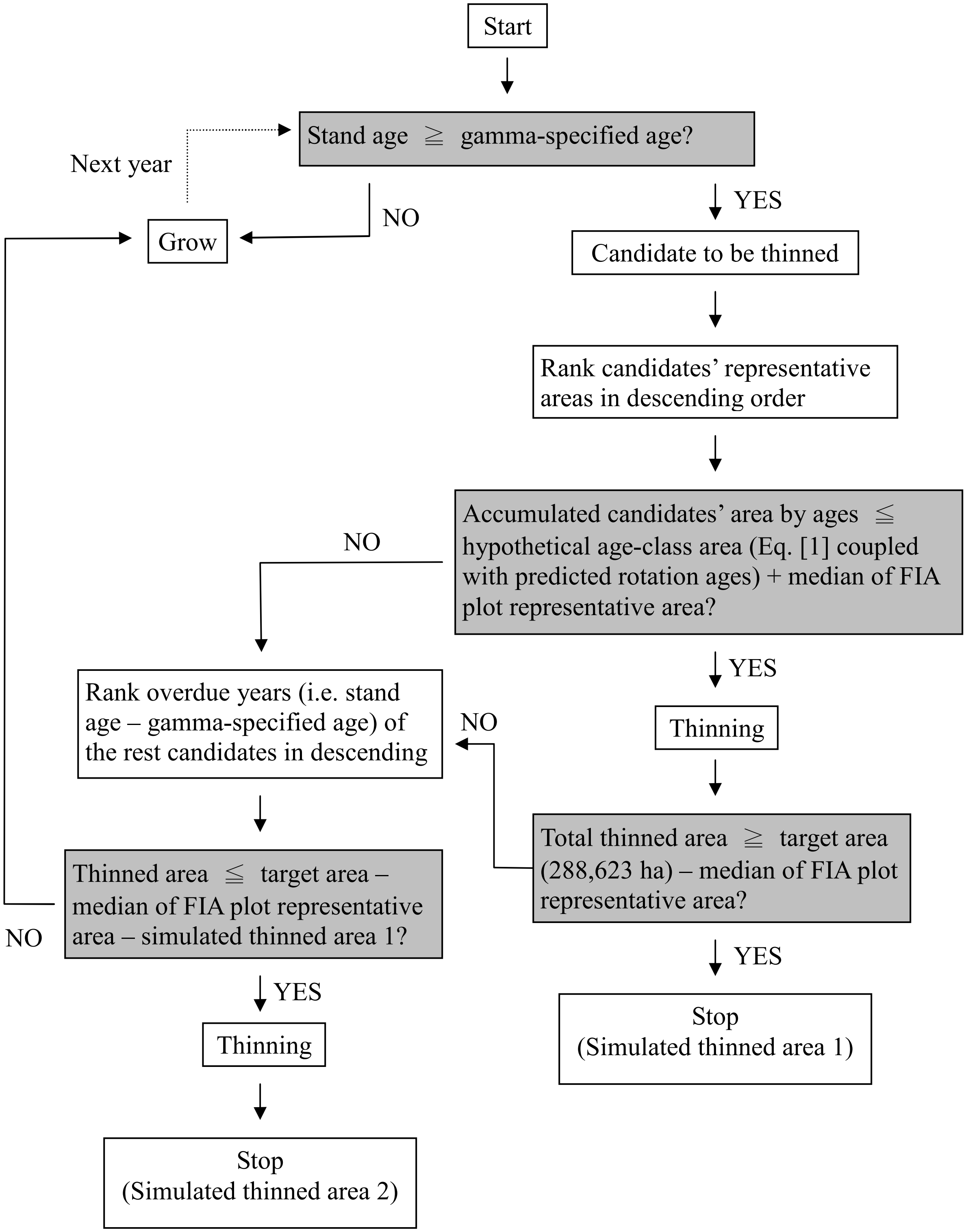

Figure 14. Rules used to select FIA plots for thinning.

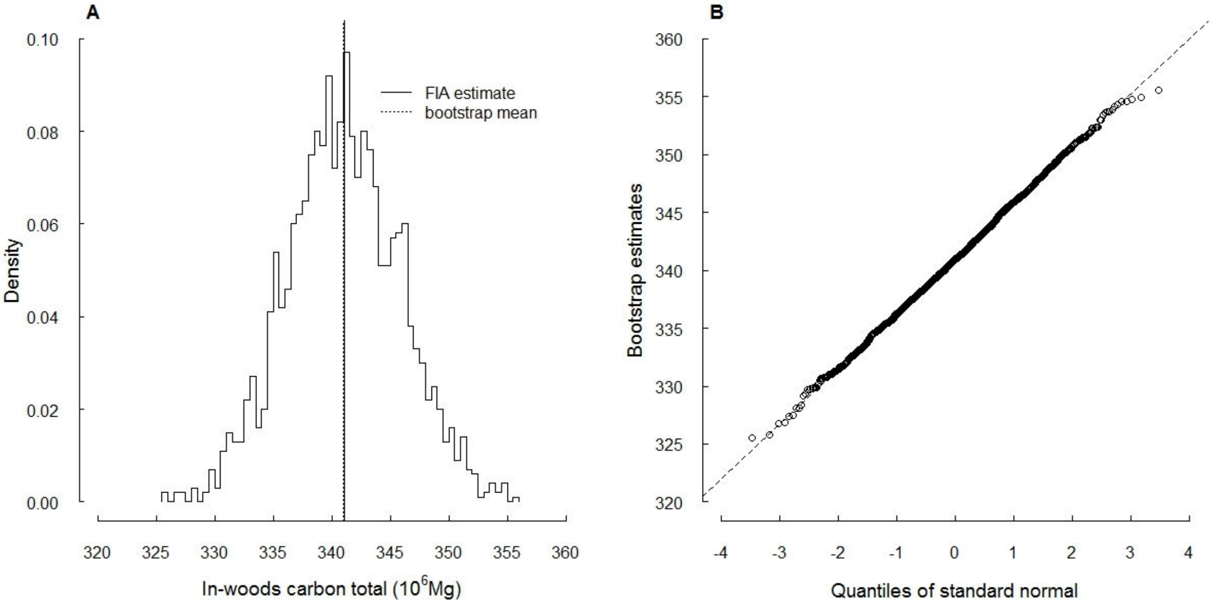

Figure 15. Bootstrap sampling distribution of southwide in-woods carbon totals (10^6 Mg) (A), and its quality of fit based on a normal distribution (B).

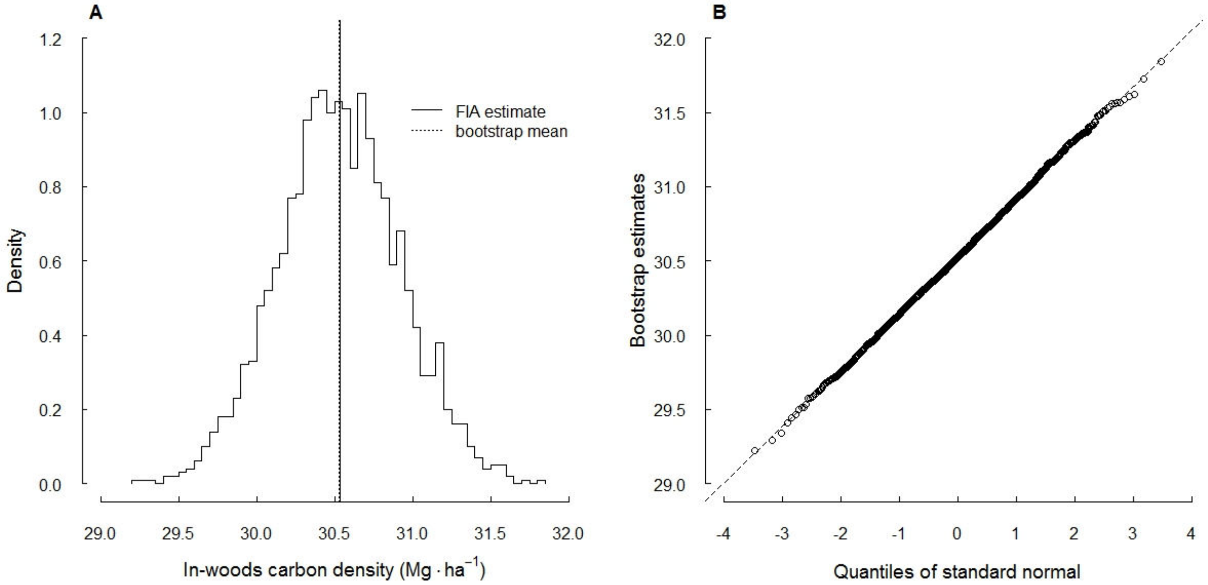

Figure 16. Bootstrap sampling distribution of southwide in-woods carbon mean per hectare ($\text{Mg}\cdot\text{ha}^{-1}$) (A), and its quality of fit based on a normal distribution (B).

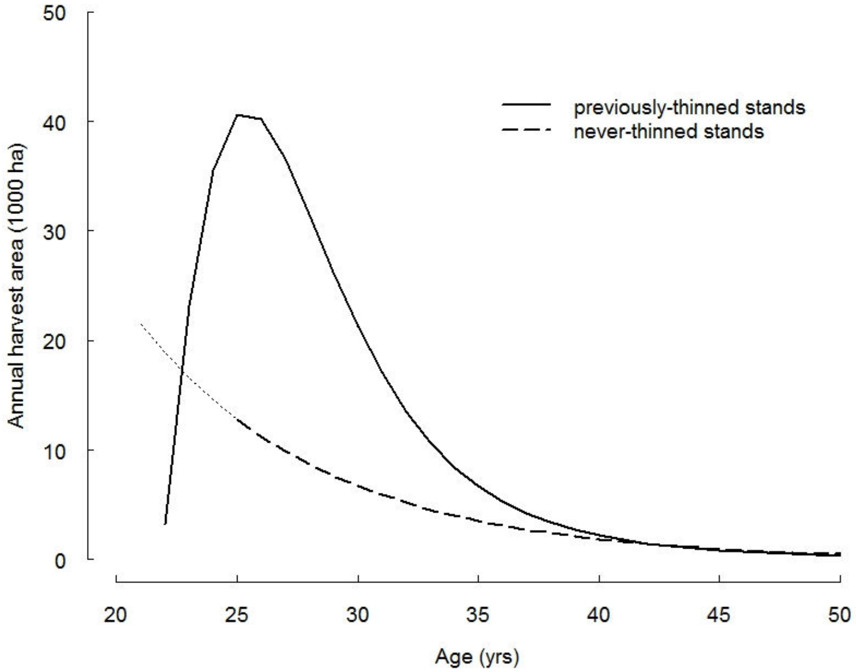

Figure 17. Hypothetical function of annual harvest area on ages, accounting for previous thinning operations. A dotted line represents that annual harvest areas may not be restricted to hypothetical values because areas of predicted rotation ages <25 are less than that of rotation age at 25 years (Figure 11B).

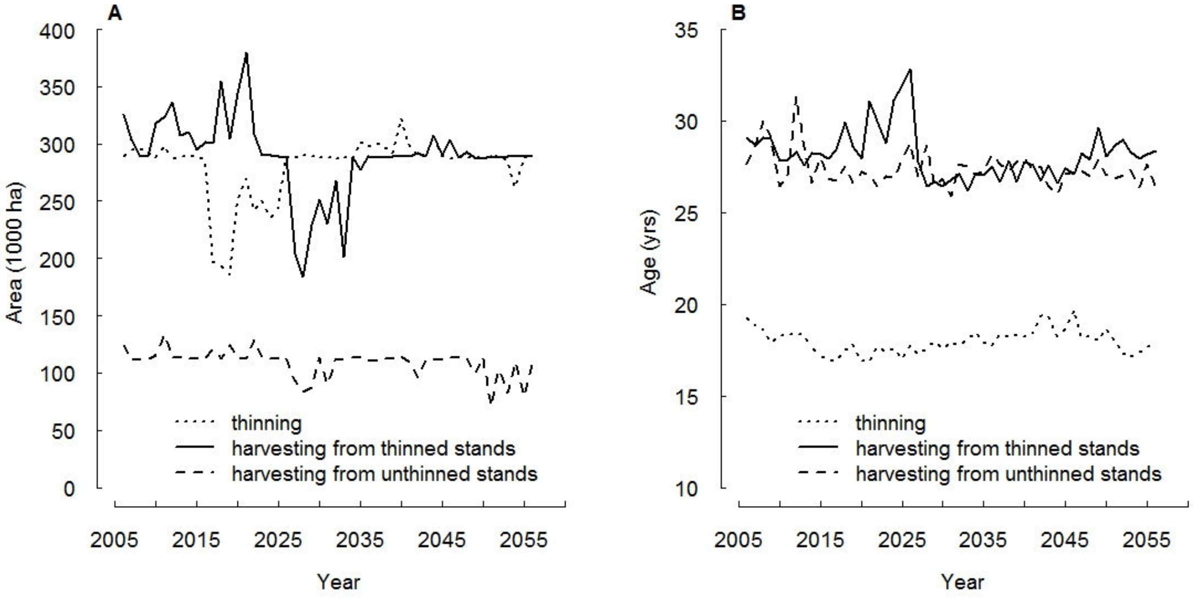

Figure 18. Simulations of area operated each year in the span of 50 years: (A) Area operated by thinning, and final harvest on thinned and unthinned stands; (B) Mean values of ages when activities of timber removed occur.

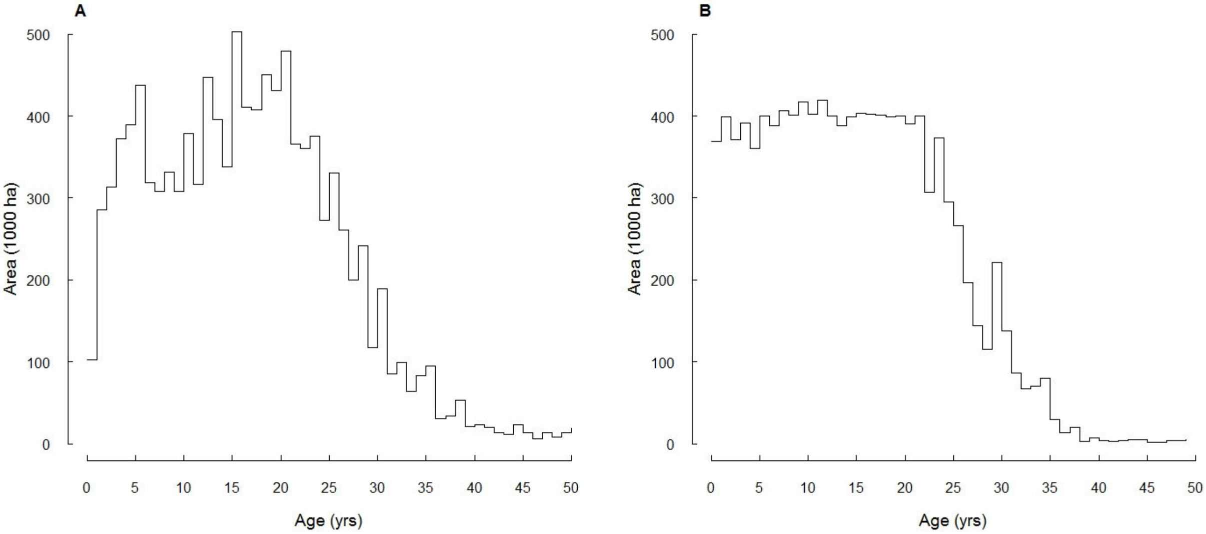

Figure 19. Age-class distribution of loblolly pine plantations throughout the South before and after a 50-year harvest period: (A) Initial plantations based on FIA 2005 – 2007 inventory data; (B) plantations after a 50-year harvest period.

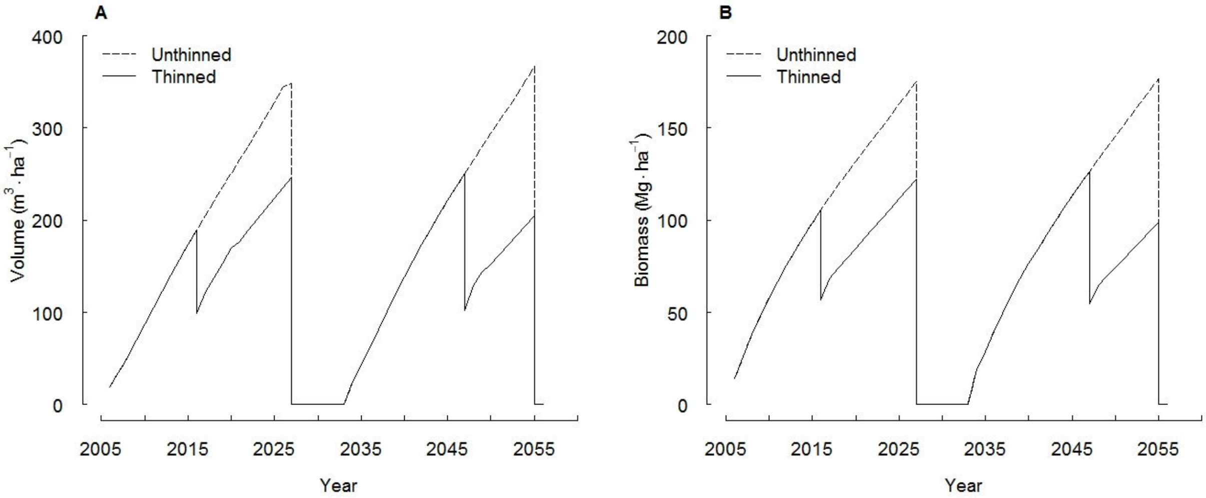

Figure 20. Temporal changes in in-woods stocks of volume (A) and aboveground biomass (B) for two different management regimes: thinned and unthinned planted loblolly pine yield and growth in 50-year projections. Two final harvests occur at age 27 years for each regime. For a thinned stand, thinnings occur at ages 16 and 19.

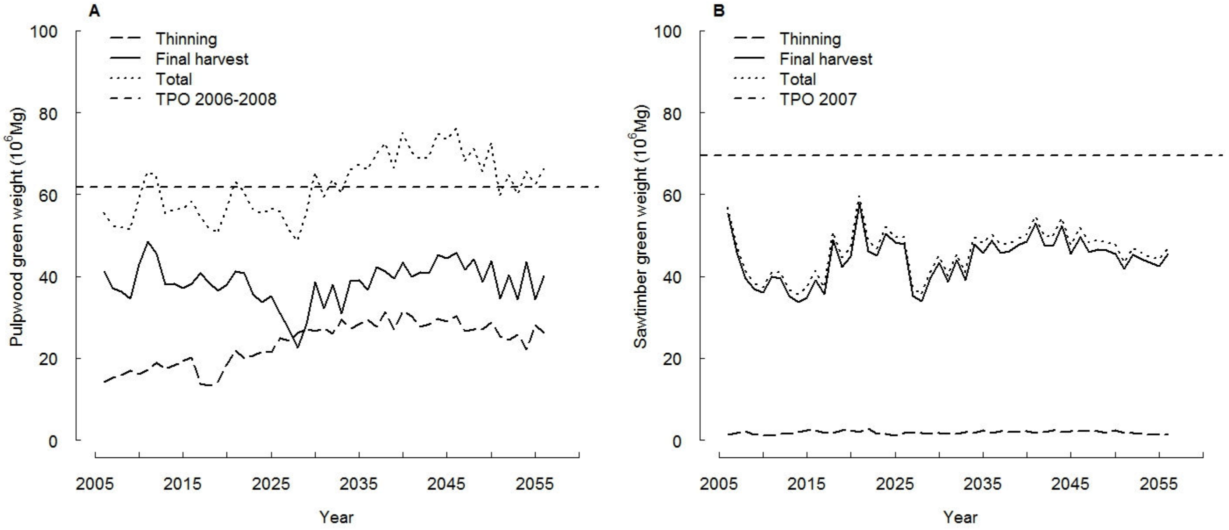

Figure 21. Timber production projections from thinnings and final harvests: (A) Pulpwood; (B) Sawtimber.

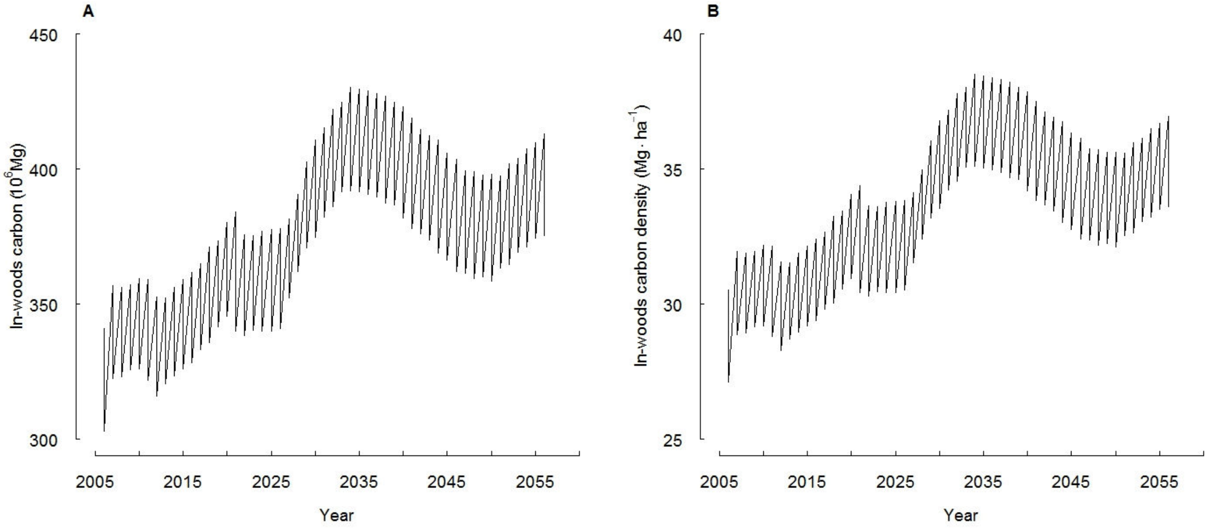

Figure 22. Effects of management activities including planting, thinning, and final harvest on the southern in-woods carbon storage: (A) Carbon total (10^6 Mg); (B) Carbon mean (Mg·ha^{-1}).

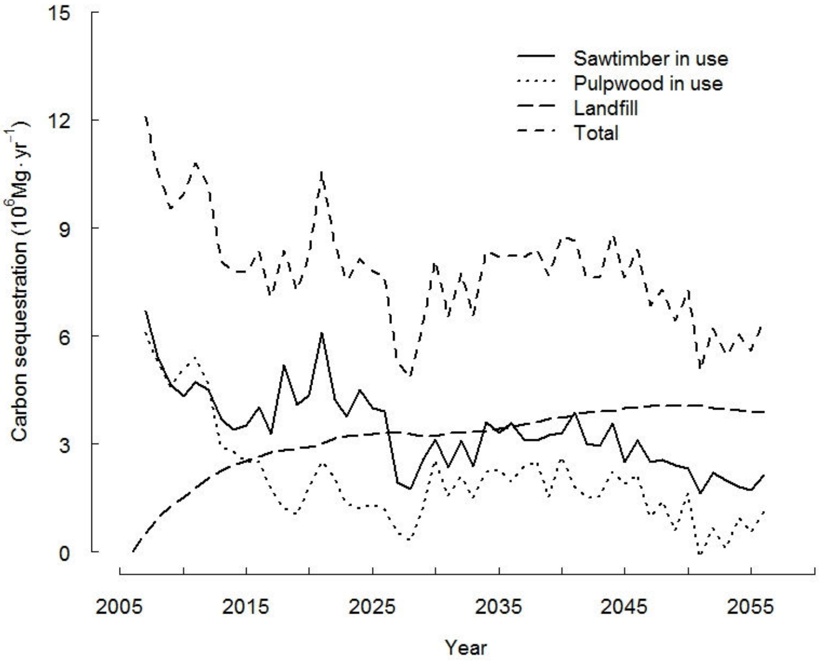

Figure 23. Carbon fluxes in harvested-wood-products pools including products in use and landfills.

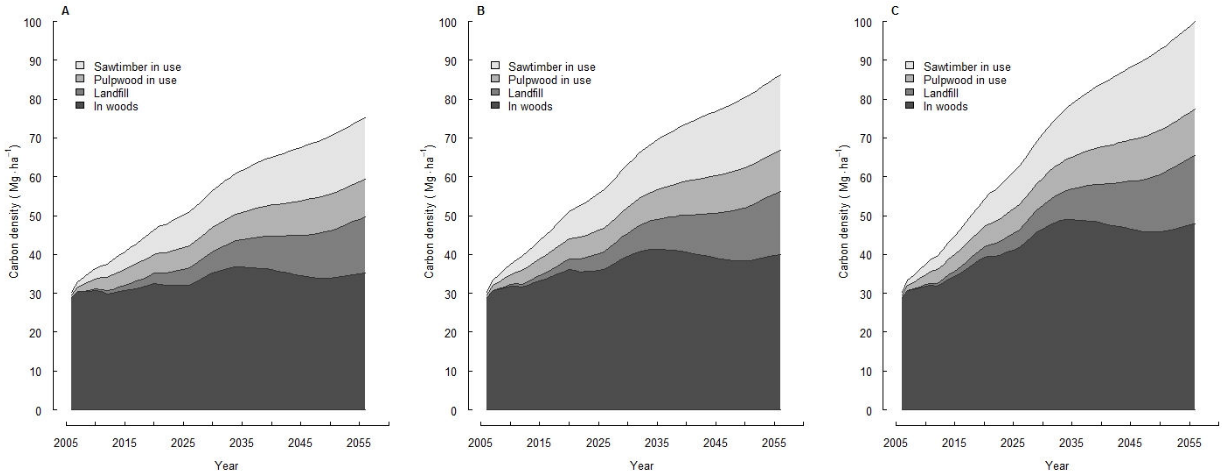

Figure 24. Effects of management intensity on carbon pools of sawtimber in use, pulpwood in use, landfill, and in woods: (A) Baseline management; (B) Management scenario 1 – fertilizer and herbicide application (plus baseline management); (C) Management scenario 2 – planting of genetically improved growing stock and fertilizer and herbicide application (plus baseline management).

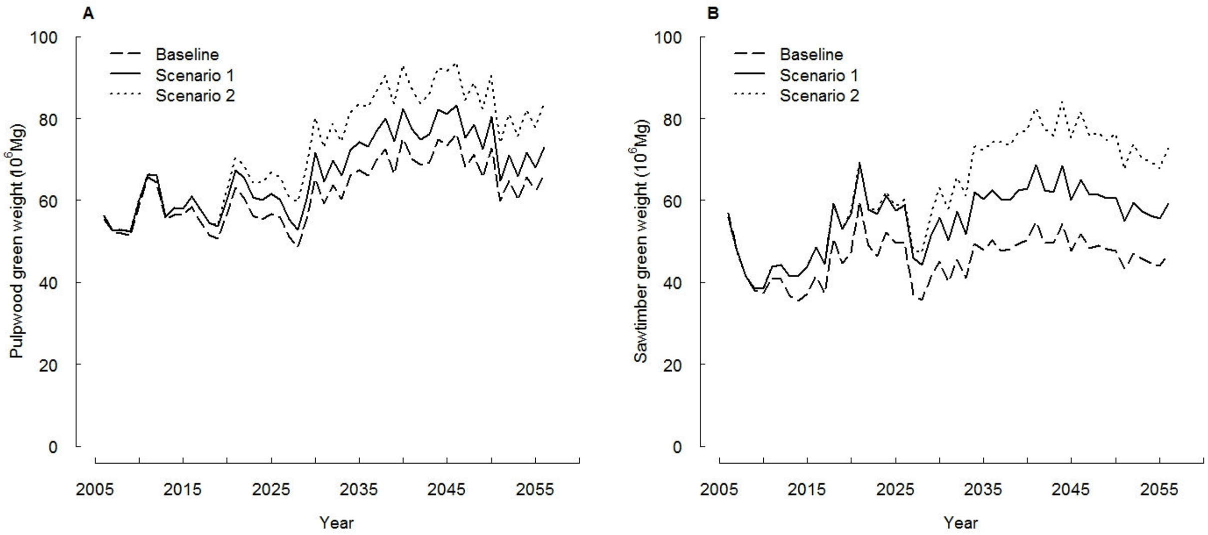

Figure 25. Effects of management intensity on timber production (A) Pulpwood green weight; (B) Sawtimber green weight.

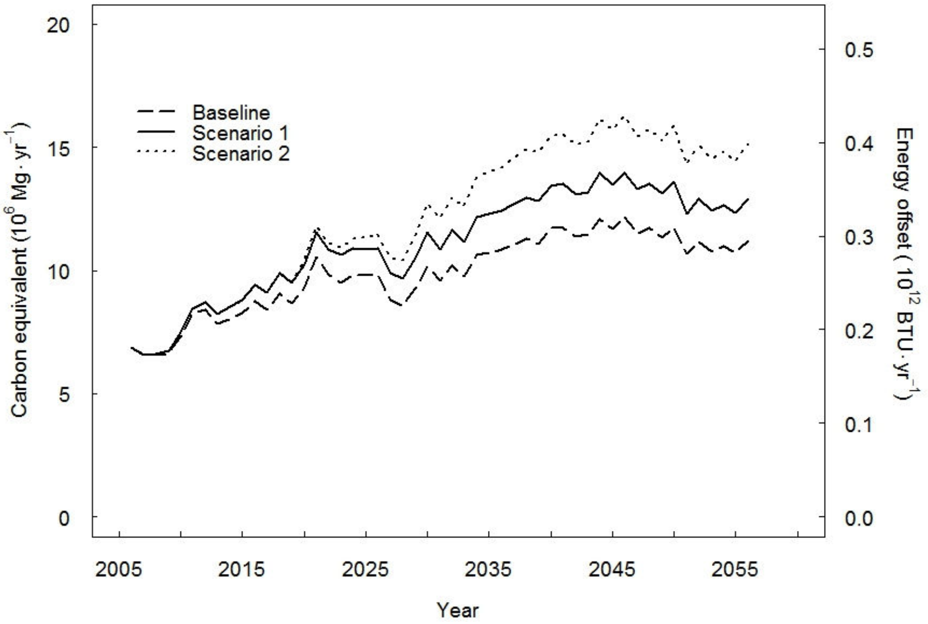

Figure 26. Effects of management intensity on energy offset and assumed energy content of biomass = 38×10^6 BTU/Mg C (U.S. Energy Information Administration, 2010).

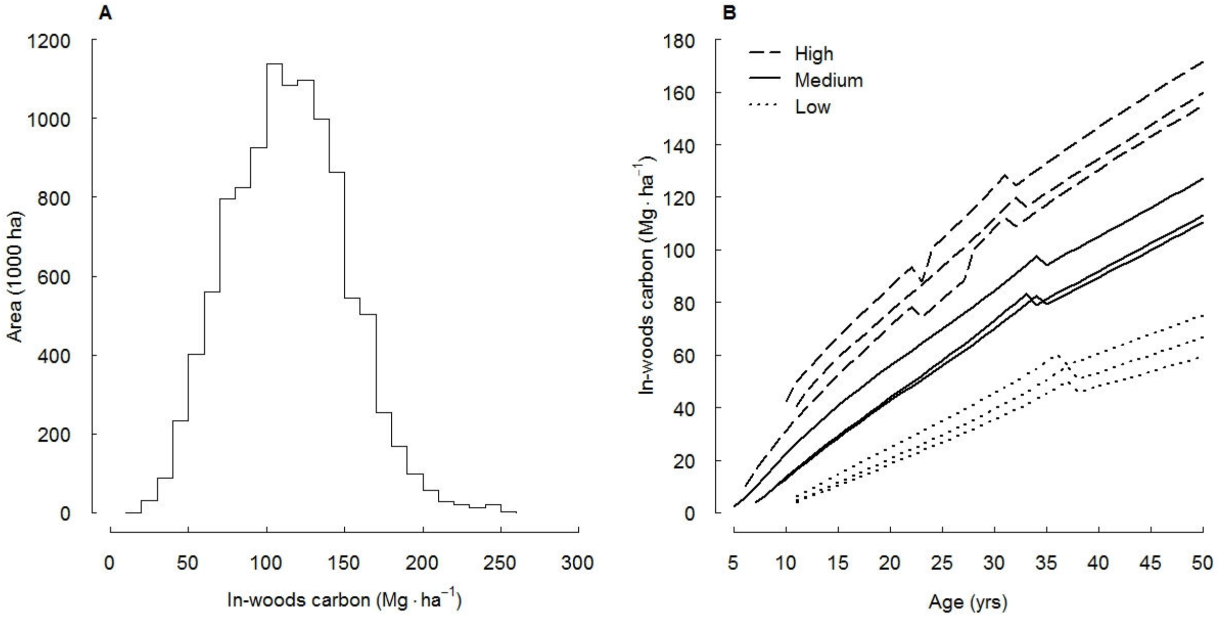

Figure 27. Hypothetical in-woods carbon mass per hectare of loblolly pine plantations across the South after a 50-year unmanaged period: (A) Distribution of carbon mass per hectare; (B) Examples of stand-level carbon mass per hectare (i.e. High, Medium, and Low) which planted stands are no longer being managed at all.

Summary and Conclusions

Regional forest inventory data from the U.S. Forest Service FIA program was linked to geospatial data and growth-and-yield models to make regional assessments of carbon storage in loblolly pine forest plantations across the South. Aboveground forest carbon pools were predicted for a collection of 5,480 FIA Phase II field plots using the stand-level model FASTLOB to account for live-tree and CWD accretion in loblolly pine plantations. Carbon in harvested wood – products in use and in landfills – was calculated using a well-vetted carbon accounting system (Smith *et al.*, 2006). Stand attributes related to forest management activities, e.g., stand age, stem density, site index, and silvicultural prescriptions such as thinning were quantified from the inventory data and used as model inputs to predict current carbon storage and project carbon storage in a 50-year time span. Plot-level carbon estimates were scaled based on FIA factors of the forest area represented by each plot, and expanded across geographic areas of interests such as counties, states, and the entire U.S. South. Bootstrap variance estimation and its corresponding Monte Carlo approximation were used to present quantitative estimates of uncertainty of in-woods carbon estimates under the current FIA data conditions. The contribution of managed forests to energy offset by burning harvested wood was similarly assessed.

Findings

The accumulation of CWD in late-rotation loblolly pine plantations across the South totaled 48.67 million metric tons of dry wood necromass, the carbon equivalent of 24.33 million metric tons. State-by-state CWD mass totals varied from 0.63 to 8.69 million Mg with the mean CWD mass per hectare of plantation forestland ranging from 6.45 to 13.31 $\mathrm{Mg \cdot ha^{-1}}$. Confidence intervals for state-level CWD dry weight per hectare generally did not exceed ± 25% of the estimated values. The spatial pattern of county-level estimates appeared to be relatively consistent with the extent of loblolly pine, with low yields near the extremes of the species' natural range and high yields in extensively-forested portions of its range. A similar trend was noted for major metropolitan areas and areas surrounding large cities in the region: e.g. Atlanta, Georgia; Charlotte, North Carolina; Houston, Texas; and Jacksonville, Florida.

In well-managed loblolly pine forestland across the South, the estimate of in-woods carbon mass total exceeded 340 million Mg, 93% from live trees and 7% from CWD. Bootstrap confidence intervals for present-day carbon storage southwide averaged 341.1×10^6 Mg (± 2.80%) for total carbon mass and 30.54 $\text{Mg}\cdot\text{ha}^{-1}$ (± 2.54%) for carbon per hectare in the in-woods pool, respectively. Compared to southwide estimates, state-by-state estimates were relatively imprecise, with bootstrap confidence intervals for states' carbon per hectare in well-managed plantation forestland spanning as much as 15% of the estimates.

In a 50-year time span, the area of simulated thinning and final harvest operations in each year of the simulation, two periods, each spanning about 10-years, reflected relatively low projected areas of thinning (2015 – 2025) and final harvest (2025 – 2035) activity. These periods corresponded to a decade of relatively low establishment of loblolly pine plantations across the South in the 1990s, which is reflected in the relatively low area of 5 – 15 year old plantations in the 2005-2007 FIA data. The annual area of final harvest averaged 400,000 ha, with 290,000 ha (± 9,600) coming from stands that were thinned during their rotation and the rest coming from plantations that were not thinned. Rotation ages in thinned stands averaged about one year more than those of unthinned stands, at 28.2 and 27.4 years, respectively. Annual area of thinning operations averaged 280,147 ha and had a standard deviation of 27,000 ha, with an average thinning age of 18.0 years ($s = 0.7$ yr).

Timber production southwide for each year was computed as an aggregate of all stand-level removals – both from thinning and end-of-rotation harvesting activities. Total pulpwood yield ranged from about 49 to 76 million green metric tons, 38% from thinning and 62% from final harvests. Sawtimber production of between 36 and 60 million green metric tons was accounted for almost entirely by end-of-rotation or "final" harvests. Compared to 2006 – 2008 TPO reports, mean of projected annual pulpwood production was nearly equivalent to the TPO report, but for sawtimber the projected mean was about 35% lower than the TPO value. Accounting for wood products' lifespans while in use and after being disposed of in landfills, harvested wood created a sink of 5 to 7 million metric tons of carbon per year. At the end of the 50-year study time span, the wood-products pool contained nearly as much carbon as the in-woods pool, with the wood-products pool showing no sign of leveling off. An average of 11 million metric tons per year of carbon is burned for energy, equivalent to 25% of annual forest-products-industry renewable energy use in U.S.A.

With the intensive management, the amount of carbon stored in all individual pools was substantially increased. Overall, intensified application of fertilizers and herbicide, and genetic improvement increased 15% of carbon storage, respectively; however, the energy used to implement increased management was not accounted for in this study. More than any other pool, the carbon stored in solid wood products derived from sawtimber increased by up to 50% under the most intensive management scenario tested. The corresponding annual energy recapture from wood products increased by up to 40% when forest management intensity was increased. By comparison, reducing plantation management intensity showed substantial gains in in-woods carbon storage, but eliminated the important carbon sink attributed to harvested wood products.

Conclusions

Attention to climate change caused by GHG emissions is increasing across the U.S.

domestic and international policy arena. Ability to link models and datasets from ongoing regional inventories is critical in making long-term projections to guide forest policy and decision making because forests have the potential to contribute significant GHG mitigation benefits. It is an open question whether the trends projected here will agree with future timber supply trajectories or forest management regimes that will be widely adopted across the South; however, the approach used here allows for flexibility and adaptability in changing assumptions or inputs when new data and information become available. The results of projections like those presented here provide potentially useful information for use in addressing questions about the role southern pine plantations can play in GHG mitigation and climate policy.

Appendix A: Disposition of carbon from industrial roundwood

Table A1. Allocation of industrial softwood roundwood to primary wood products in the southern U.S.A. based on Table D6 from Smith et al. (2006)

Region	Category	Lumber	Plywood	Oriented strandboard	Non-structural panels	Other industrial products	Wood pulp	Fuel and other emissions
Southeast	Sawtimber	0.350	0.076	0.000	0.027	0.054	0.129	0.364
	Pulpwood	0.000	0.000	0.103	0.004	0.000	0.447	0.447
South Central	Sawtimber	0.324	0.130	0.000	0.019	0.023	0.133	0.371
	Pulpwood	0.000	0.000	0.135	0.006	0.000	0.430	0.430

Table A2. Fraction of carbon in primary wood products remaining in end uses up to 50 years after production† based on Table 8 from Smith et al. (2006).

Year after production	Lumber	plywood	Oriented strandboard	Non-structural panels	Other industrial products	Wood pulp
0	1.000	1.000	1.000	1.000	1.000	1.000
1	0.973	0.976	0.983	0.969	0.944	0.845
2	0.947	0.952	0.967	0.939	0.891	0.713
3	0.922	0.930	0.952	0.911	0.841	0.603
4	0.898	0.909	0.937	0.883	0.794	0.509
5	0.875	0.888	0.922	0.857	0.749	0.430
6	0.854	0.869	0.908	0.832	0.707	0.360
7	0.833	0.850	0.895	0.808	0.667	0.299
8	0.813	0.832	0.881	0.785	0.630	0.243
9	0.795	0.815	0.869	0.763	0.595	0.192
10	0.777	0.798	0.856	0.741	0.561	0.149
11	0.760	0.782	0.844	0.721	0.530	0.115
12	0.743	0.767	0.832	0.701	0.500	0.088
13	0.728	0.752	0.821	0.683	0.472	0.068
14	0.712	0.738	0.810	0.665	0.445	0.052
15	0.698	0.724	0.799	0.647	0.420	0.040
16	0.684	0.711	0.789	0.630	0.397	0.030
17	0.671	0.698	0.778	0.614	0.375	0.023
18	0.658	0.685	0.768	0.599	0.354	0.018
19	0.645	0.673	0.759	0.584	0.334	0.013
20	0.633	0.662	0.749	0.569	0.315	0.009
21	0.622	0.650	0.740	0.555	0.297	0.006
22	0.611	0.639	0.731	0.542	0.281	0.005
23	0.600	0.629	0.722	0.529	0.265	0.004
24	0.589	0.619	0.713	0.517	0.250	0.003
25	0.579	0.609	0.705	0.505	0.236	0.002
26	0.569	0.599	0.697	0.493	0.223	0.002
27	0.560	0.589	0.689	0.482	0.210	0.001
28	0.551	0.580	0.681	0.471	0.198	0.001
29	0.542	0.571	0.673	0.460	0.187	0.001
30	0.533	0.563	0.666	0.450	0.177	0.001

Year after production (cont.)	Lumber	Plywood	Oriented strandboard	Non-structural panels	Other industrial products	Wood pulp
31	0.525	0.554	0.658	0.440	0.167	0.000
32	0.517	0.546	0.651	0.431	0.157	0.000
33	0.509	0.538	0.644	0.421	0.149	0.000
34	0.501	0.530	0.637	0.412	0.140	0.000
35	0.494	0.522	0.630	0.404	0.132	0.000
36	0.487	0.515	0.623	0.395	0.125	0.000
37	0.480	0.508	0.617	0.387	0.118	0.000
38	0.473	0.500	0.610	0.379	0.111	0.000
39	0.466	0.493	0.604	0.372	0.105	0.000
40	0.459	0.487	0.598	0.364	0.099	0.000
41	0.453	0.480	0.592	0.357	0.094	0.000
42	0.447	0.474	0.586	0.350	0.088	0.000
43	0.441	0.467	0.580	0.343	0.083	0.000
44	0.435	0.461	0.574	0.337	0.079	0.000
45	0.429	0.455	0.568	0.330	0.074	0.000
46	0.423	0.449	0.563	0.324	0.070	0.000
47	0.418	0.443	0.557	0.318	0.066	0.000
48	0.413	0.437	0.552	0.312	0.063	0.000
49	0.407	0.432	0.546	0.306	0.059	0.000
50	0.402	0.426	0.541	0.301	0.056	0.000

[†] Softwood

Table A3. Fraction of carbon in primary wood products remaining in landfills up to 50 years after production† based on Table 9 from Smith et al. (2006).

Year after production	Lumber	plywood	Oriented strandboard	Non-structural panels	Other industrial products	Wood pulp
0	0	0	0	0	0	0
1	0.018	0.016	0.011	0.021	0.037	0.051
2	0.035	0.032	0.021	0.04	0.072	0.093
3	0.051	0.046	0.032	0.059	0.104	0.128
4	0.067	0.06	0.041	0.076	0.134	0.155
5	0.081	0.073	0.05	0.093	0.163	0.178
6	0.094	0.085	0.059	0.108	0.189	0.196
7	0.107	0.096	0.068	0.123	0.213	0.211
8	0.119	0.107	0.076	0.137	0.236	0.225
9	0.13	0.118	0.084	0.151	0.257	0.236
10	0.141	0.128	0.091	0.163	0.277	0.245
11	0.151	0.137	0.098	0.176	0.296	0.251
12	0.161	0.146	0.105	0.187	0.313	0.254
13	0.17	0.155	0.112	0.198	0.329	0.255
14	0.178	0.163	0.118	0.208	0.344	0.255
15	0.187	0.171	0.124	0.218	0.357	0.253
16	0.194	0.178	0.13	0.227	0.37	0.251
17	0.202	0.185	0.136	0.236	0.382	0.248
18	0.209	0.192	0.142	0.245	0.393	0.245
19	0.215	0.199	0.147	0.253	0.403	0.242
20	0.222	0.205	0.152	0.261	0.413	0.239
21	0.228	0.211	0.157	0.268	0.422	0.235
22	0.234	0.217	0.162	0.275	0.43	0.232
23	0.239	0.222	0.167	0.282	0.438	0.228
24	0.245	0.227	0.171	0.288	0.445	0.224
25	0.25	0.233	0.176	0.294	0.451	0.221
26	0.255	0.238	0.18	0.3	0.457	0.218
27	0.259	0.242	0.184	0.306	0.463	0.214
28	0.264	0.247	0.188	0.311	0.468	0.211
29	0.268	0.251	0.192	0.316	0.473	0.209
30	0.272	0.256	0.196	0.321	0.477	0.206

Year after production (cont.)	Lumber	Plywood	Oriented strandboard	Non-structural panels	Other industrial products	Wood pulp
31	0.276	0.26	0.2	0.326	0.481	0.203
32	0.28	0.264	0.204	0.33	0.485	0.2
33	0.284	0.268	0.207	0.335	0.488	0.198
34	0.287	0.272	0.211	0.339	0.491	0.196
35	0.291	0.275	0.214	0.343	0.494	0.194
36	0.294	0.279	0.217	0.347	0.497	0.191
37	0.298	0.282	0.221	0.35	0.499	0.189
38	0.301	0.286	0.224	0.354	0.502	0.187
39	0.304	0.289	0.227	0.357	0.504	0.186
40	0.307	0.292	0.23	0.361	0.506	0.184
41	0.31	0.295	0.233	0.364	0.507	0.182
42	0.312	0.298	0.236	0.367	0.509	0.181
43	0.315	0.301	0.239	0.37	0.51	0.179
44	0.318	0.304	0.241	0.373	0.512	0.178
45	0.32	0.307	0.244	0.376	0.513	0.176
46	0.323	0.309	0.247	0.378	0.514	0.175
47	0.325	0.312	0.249	0.381	0.515	0.174
48	0.328	0.315	0.252	0.384	0.516	0.173
49	0.33	0.317	0.255	0.386	0.516	0.172
50	0.332	0.32	0.257	0.388	0.517	0.171

† Softwood

Table A4. Coefficients for fraction of carbon emitted with energy recapture for industrial softwood roundwood based on Table D7 from Smith et al. (2006).

Region	Category	Coefficients†		
		a	*b*	*c*
Southeast	Sawtimber	0.7149	1313	0.6051
	Pulpwood	0.6179	3630	0.5054
South Central	Sawtimber	0.6136	1264	0.6634
	Pulpwood	0.619	3455	0.5148

† Estimates are calculated according to:

$$fraction = a \times \exp\left(-\left(year/b\right)^{c}\right)$$