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Modeling production and decay of coarse woody debris in loblolly pine plantations

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ABSTRACT

Forest management can have large impacts on the production and yield of coarse woody debris (CWD) in terrestrial ecosystems, yet few modeling tools exist to inform such efforts. The goal here was to develop a set of prediction equations for use in conjunction with loblolly pine (*Pinus taeda* L.) modeling and inventory systems to estimate CWD yields at scales ranging from individual trees to whole plantations. Permanent field plots from a 21-year study of thinning effects on plantation growth and yield across the commercial range of the species in the southern United States were surveyed to obtain sample data on CWD volume, density, and mass. Measured CWD properties were combined with inventory records of tree mortality over the study duration to characterize CWD production, decay and yield in a series of prediction equations. The resulting equations predict CWD attributes of dead trees including dry weight (kg) and fraction of standing versus downed woody material based on the time since death (years), tree diameter at breast height (cm) and height (m) at time of death and geographic coordinates of latitude and longitude. A stand-level equation predicts total CWD yield (Mg ha^{-1}) for thinned or unthinned stands based on plantation age, stem density (trees ha^{-1}), and the average height of dominant and codominant trees (m). Piece-level equations predict dry density (kg m^{-3}) or nitrogen concentration (%) of CWD pieces based on their position (standing or down), ordinal decay classes, and latitude. The tree and stand-level prediction equations are designed for use in GIS or growth and yield modeling systems. The piece-level equations are designed to be used in inventory applications that survey CWD. The equations should facilitate the accurate and facile determination of mass, carbon, and nitrogen contents of CWD in planted loblolly pine forests of the southern United States.

1. Introduction

Carbon storage in forests is a subject of considerable importance, as scientists and policy makers seek to improve understanding of terrestrial carbon cycles and manage the role of forests in regional and global carbon budgets. International efforts aimed at reducing atmospheric concentrations of greenhouse gasses depend on accurate models to assess the extent of various sinks and sources of such gasses, including carbon dioxide (UNFCCC, 1992). These models in turn rely on knowledge about carbon storage and fluxes from terrestrial carbon pools such as soil organic carbon, belowground biomass (root systems), aboveground biomass, and detritus—a major component of which is usually called coarse woody debris or CWD (Cannell et al., 1985). Recent efforts have increasingly addressed knowledge gaps of how CWD contributes to forest carbon cycles and regional or global carbon budgets (Yin, 1999; Brown, 2002; Sun et al., 2004). Still, gaps exist regarding the impacts of forest management practices on the production and decay of CWD.

It is known that forest management has substantial impacts on CWD production and decay, yet information is incomplete to accurately model these impacts where they may have the potential to assist with managing carbon budgets (Krankina and Harmon, 1995; Duvall and Grigal, 1999; Currie and Nadelhoffer, 2002; Janisch and Harmon, 2002). To date, much attention has been paid to assessments of carbon at national or continental scales (Turner et al., 1995; Goodale et al., 2002). Different information may be required to manage carbon at forest or landscape scales, especially in silvicultural systems that are intensively managed. Such is the case in the loblolly pine (*P. taeda* L.) plantation ecosystems of the

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southeastern United States, where few efforts have been made to model CWD production and decay rates at scales that would be useful to enterprise managers (Van Lear, 1993; Radtke et al., 2004).

Loblolly pine is the most commercially important species grown in the southern United States, comprising over 1.7 billion m^3 of growing stock. Southern pine forests cover nearly 20 million ha from eastern Texas to Maryland. Loblolly pine has become the most widely planted species in the southern U.S., with plantations covering over 8 million ha. The southern pine resource is expected to supply a large portion of the fiber needs of the United States in the next four decades, with both the area in pine plantations and the intensity of plantation management projected to increase (Prestemon and Abt, 2002).

In response to the increasing recognition of the need for regional assessments of forest detritus, the U.S. Department of Agriculture (USDA) Forest Service incorporated indicators of CWD and other dead plant materials into its national Forest Inventory and Analysis (FIA) program in 1999 (Coulston et al., 2005). In conjunction with FIA estimates based on Phase II field sample plots, the Forest Service now conducts sample-based assessments of aboveground dead wood and litter mass over much of the United States (Chojnacky and Heath, 2002; Chojnacky et al., 2004; Chojnacky and Schuler, 2004). We define CWD to include the contents of standing dead trees having a diameter at breast height $\geq$7.6 cm, plus the contents of leaning or fallen dead tree stems having a large-end diameter $\geq$7.6 cm. The FIA program estimates standing CWD from standing dead trees, called snags, measured on field sample plots in the inventory's Phase II. Estimates of downed CWD are obtained from sample data measured on fallen dead trees, called logs, selected using line-intercept methods in a subset of Phase II field plots known as Phase III (Woodall and Williams, 2005).

The FIA program does not aim to provide detailed estimates that can be used to manage silvicultural systems on individual stands or tracts of land; however, FIA inventory data have previously been used to develop modeling systems that can be used in stand or tract-level applications (Donnelly et al., 2001). Several studies have addressed the role that FIA Phase III data and estimates may serve for development of models to guide broad-scale forest policy and management decisions relating to CWD (Heath and Birdsey, 1993; Smith et al., 2003). Few, if any, data sets are known to exist that could be used to develop detailed models that link forest management to CWD production and decomposition. As the need for information about carbon stocks and fluxes continues to grow, and as management pertaining to carbon focuses on smaller land units and shorter time intervals, the range of modeling tools available must expand to satisfy these needs (Radtke et al., 2004).

The purpose of this study was to develop a set of prediction models for estimating the production and decomposition of CWD in loblolly pine plantation ecosystems of the southern United States. A guiding principle of the research was the ability to produce results that could be linked to existing forest stand modeling systems. This will allow forest managers to pursue objectives related to CWD production and carbon storage. To that end, two capabilities were identified as essential, including (1) the ability to dynamically predict the mass and carbon contents in dead plantation trees based on CWD decay rates and the passage of time, and (2) the ability to estimate stand-level CWD yield over time and for various stand conditions, based on predictors that would normally be available from standard forest inventory data. A third capability was identified, that results could be linked to existing inventory systems, namely the ability to estimate properties of individual CWD elements – their density, mass, and nitrogen contents – from standard observational variables such as those acquired in FIA Phase II and Phase III surveys.

2. Materials and methods

2.1. Field data

CWD Data were collected in 2003 from 36 research sites established in loblolly pine plantations across the geographic region where the species is planted for commercial production in the southern United States (Fig. 1). These study sites were all that remained at the completion of a region-wide loblolly pine growth and yield thinning experiment established in 1980–1982 that initially consisted of 186 study sites (Burkhart et al., 1985; Amateis et al., 1996, 2006). Stand ages at time of establishment ranged from 8 to 25, with a mean age of 15 years. At each study site, three plots were established. A 0.04 ha control plot was never thinned and two 0.09 ha treatment plots were thinned according to light (approximately 1/3 of the basal area removed) and heavy (approximately 1/2 of the basal area removed) thinning intensities. All trees in the control plots and the residual trees following thinning in thinned plots were tagged and mapped based on their *x–y* coordinates in the plot. Measurements of diameter at breast height (*dbh*) and height were collected at establishment and subsequently every 3 years. Mortality of individual trees was also observed at each 3-year remeasurement, with the exact year of mortality unknown but being limited to one of the 3 years between field measurements. Field workers thus used clues about the physical condition of dead trees, e.g., persistence of needles and fine twigs, to estimate the exact year of death as either zero, 1, or 2 years prior to most recent growing season. When no information was recorded, the year of death was set to the midpoint year of the measurement interval to ensure no more than 1 year of error in quantifying the year of death.

From the database generated over the duration of the thinning study, a list of loblolly pine trees that died prior to 2003 was compiled for each of the 36 remaining sites. The last live measurements of *dbh* and total height for each tree along with tree *x–y* coordinates were used to locate and positively identify dead trees representing a range of tree sizes and years since death. Some dead trees were found whole; others were found in multiple pieces. Each piece was categorized into one of five decay classes following Pyle and Brown (1998), and one of two position classes following USDA Forest Service Forest Inventory and Analysis (FIA) classifications of "snag" (CWD standing upright or leaning $<45^\circ$ from vertical) or "log" (CWD leaning $\geq 45^\circ$ from vertical or in contact with the ground). To test the efficacy of these position classifications for modeling CWD decomposition, we defined additional position categories to extend the 2-position system into four categories: (1) snag standing upright or leaning $<45^\circ$ from vertical; (2) snag leaning $\geq 45^\circ$ from vertical; (3) log making ground contact at two or more points along its length; (4) log covered by leaf litter. Some breakage was ignored when decay class, position, and spatial orientation of logs were identical in adjacent pieces. In all, 964 pieces of CWD were classified by this system. Subsequently, measurements of length and diameter at large and small ends were recorded for each piece of CWD.

In total, 1000 dead trees were relocated over the 36 study sites. Among these, only 762 were classified as having measurable CWD persisting in decay classes 1–5. The other 238 were classified as "forest floor" trees (Little and Ohmann, 1988), no longer containing measurable CWD due to their advanced stages of decomposition. Confirmation of the existence of forest-floor trees was aided by stem maps and inventory records of tree sizes and their approximate year of death.

Wood specimens were collected on a subsample of 849 (of 964) CWD pieces from 662 (of 762) dead trees (Table 1). Subsample intensity was deemed adequate on a particular study