Deriving forest canopy fuel parameters for loblolly pine forests in eastern Texas

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Abstract: Crown fires, the fastest spreading of all forest fires, can occur in any forest type throughout the world. The overall aim of this study was to estimate forest canopy fuel parameters including canopy bulk density and canopy base height for loblolly pines (Pinus taeda L.) at the plot level using both allometric equations and CrownMass/FMAPlus software. Allometric equation results were compared with the CrownMass outputs for validation. According to our results, the calculated average canopy bulk density values, across all 50 plots, were 0.18 and 0.07 kg/m³ for the allometric equation and the CrownMass program, respectively. Lorey’s mean height approach was used in this study to calculate canopy base height at the plot level. The average height values of canopy base height obtained from the Lorey height approach was 10.6 m and from the CrownMass program was 9.1 m. The results obtained for the two methods are relatively close to each other, with the estimate of canopy base height being 1.16 times larger than the CrownMass value. This study provides a practical method for quantifying these parameters and making them directly available to fire managers. The accuracy of these parameters is very important for realistic predictions of wildfire initiation and growth.

Résumé : Les feux de cimes, les feux de forêt qui se propagent le plus rapidement, peuvent survenir dans n’importe quel type de forêt partout dans le monde. L’objectif global de cette étude consistait à estimer les paramètres des combustibles dans le couvert forestier, incluant la densité apparente du couvert et la hauteur de la base du couvert pour les pins à encens (Pinus taeda L.) à l’échelle de la placette, à l’aide des équations allométriques et du module CrownMass du logiciel FMAPlus. Les résultats de l’équation allométrique ont été comparés à ceux du module CrownMass à des fins de validation. Selon nos résultats, les valeurs moyennes calculées de la densité apparente du couvert pour l’ensemble des 50 placettes étaient respectivement de 0,18 et 0,07 kg/m³ pour l’équation allométrique et le module CrownMass. L’approche de Lorey pour la hauteur moyenne a été utilisée dans cette étude pour calculer la hauteur de la base du couvert à l’échelle de la placette. Les valeurs de hauteur moyenne de la base du couvert étaient de 10,6 m selon l’approche de Lorey et de 9,1 m selon le module CrownMass. Les résultats obtenus avec les deux méthodes sont relativement proches l’un de l’autre ; la valeur de la hauteur de la base du couvert estimée par l’approche de Lorey est 1,16 fois plus grande que celle obtenue avec le module CrownMass. Cette étude fournit une méthode pratique pour quantifier ces paramètres et les rendre directement disponibles pour les gestionnaires du feu. La fiabilité de ces paramètres est très importante pour prédire de façon réaliste l’initiation et le développement des feux de forêt.

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Introduction

Wildland crown fires are one of the most important and prevalent types of disasters because of their potential environmental impacts (Pyne et al. 1996). In recent years, the number of crown fires has significantly increased, threatening life, property, and natural resources in the world (Falkowski et al. 2005). Fire managers and foresters use the term “crown” to refer to the branches and foliage of individual trees and the term “canopy” refers to the aggregation of crowns at the stand level (Scott and Reinhardt 2001).

Canopy fuels are defined as all burnable materials, which include live and dead foliage, lichen, and redundant stem and branchwood located in the upper forest canopy (Chu-
The CBD and CBH have been modeled for various species using allometric equations to predict crown fire behavior and spread for different regions worldwide. However, none of these studies used species-specific equations for calculating crown volume and foliage biomass when calculating CBD at the stand level. Species type plays an important role in calculating the CBD canopy fuel parameter (Brown 1978; Baldwin and Peterson 1997). Crown shape is an important determinant of crown volume (Baldwin and Peterson 1997) and it varies by species. There is a need to accurately predict the crown shape for specific species. To improve the prediction of CBD, species-specific equations are used in this study. Many studies use an assumption for crown shape and crown volume equations accordingly (i.e., Monserud and Marshall 1999; Riaño et al. 2003; Andersen et al. 2005; Hall and Burke 2006). These assumptions tend to result in the overestimation of crown volume because they include the space occupied by the canopy fuels (foliated) and the space not occupied by the canopy fuels (nonfoliated) in the tree crown (Fig. 2a). In this study, using the equations from Baldwin and Peterson (1997), crown volume for loblolly pines was estimated by considering only the space occupied by the canopy fuels (Fig. 2b).

Unlike tree crown base height (CrBH), CBH is a complex stand-level variable that is not easily measured in the field (Van Wagner 1993). One of the assumptions made when estimating CBH is that the canopy biomass is distributed uniformly within the canopy stand, which is unlikely even in stands with simple structures (Scott and Reinhardt 2001). These assumptions can lead to poorly defined CBH and CBD (Sando and Wick 1972; Hall and Burke 2006). Neither the lowest CrBH in a stand nor the arithmetic average of CrBH is likely to represent the stand as a whole. Therefore, Lorey’s mean height was used in this study to calculate CBH. This method weights the contribution of trees to the stand height by their basal area by allowing the bigger trees to contribute more to the mean (Philip 2002). The key in defining CBH for the purpose of modeling fire behavior is, for a given stand, to choose that height at which a fire is likely to move from the surface to the canopy and then to be carried by the canopy. This depends on many factors including fire intensity and wind speed. Fire has a spatial component, so it is unlikely that the best choice is the lowest CBH, as the occurrence of fire under that particular tree is less likely than it is under other trees in the stand. It is also unlikely to be the arithmetic average of the CBH.

Loblolly pine is a very common species in the southeastern United States. One third of the south is covered by this spe-
cies including 12 southern states from central Texas to Virginia (Doran et al. 2009). To our knowledge, there are no published studies that have used species-specific equations for calculating crown volume and foliage biomass when calculating CBD at stand level. Mutlu et al. (2008) derived a surface fuel model map, which is one of the key inputs for fire simulation software for the same area. The full area coverage maps of CBD and CBH are the other two required key data inputs for crown fire simulation. The overall aim of this study was to estimate CBD and CBH for loblolly pine trees in eastern Texas at the plot level using both species-specific allometric equations and CrownMass/FMAPlus software. In this study, allometric equation results were compared with the results of CrownMass/FMAPlus software for validation.

Materials and methods

Study area

The study area is located in eastern Texas near Huntsville covering about 47.15 km² (approximately 4800 ha) and contains part of the Sam Houston National Forest. Vegetation in the study area comprises upland, bottomland hardwoods, coniferous, old-growth pine stands, mixed stands, shrubs, upland and bottomland hardwoods, and open ground with grass. This study area was selected because it has a diverse range of vegetation types with varying degrees of understory vegetation density, which relates to different fuel models. The area was also highly accessible for field data collection to estimate both surface fuel models and canopy fuel parameters. The study area has gentle slopes with a 90 m average elevation. Figure 3 represents the high-resolution (2.5 m × 2.5 m) multispectral QuickBird image of the study area. The white marks (yellow marks online) on the image illustrate the locations of field plots within the study area. The overall steps of this study are illustrated in Fig. 4. The area has a diverse range of vegetation types with varying degrees of understory vegetation density, which relate to different fuel models. The area was also highly accessible for field data collection.

Field data collection

Field data were collected from 50 plots between May 2004 and July 2004. Ground reconnaissance was used to identify the potential plot locations in Huntsville, Texas. Plot locations were determined by specialists from the Texas Forest Service taking into account (i) ease of access to each plot, (ii) land ownership (private or federal), and (iii) cover a variety of vegetation types. Two different-sized circular plots were used in this study: a larger plot with a radius of 11.35 m (37.24 ft) covering 404.7 m² and a smaller plot with a radius of 3.59 m (11.78 ft) covering 40.468 m². The smaller plot size was used in the young unthinned loblolly pine plantations. The plot center coordinates were recorded with a GeoExplorerXT and were differentially corrected with Trimble’s Pathfinder software. The accuracy of our GPS unit is 2–5 m. Inside each plot boundary, the following parameters were measured for each tree: diameter at breast height (DBH), total tree height, CrBH, and crown class. To map each tree’s location, distance (metres) and azimuth from the center of the plot were measured starting from north and progressing clockwise. A Haglöf Vertex III hypsometer was used to measure total tree height and CrBH. CrBH was measured as the distance from the ground to the first live branch or whorl. A diameter tape was used to determine each tree’s DBH. The Kraft system was used to classify each tree’s crown: dominant, codominant, intermediate, and suppressed (Mutlu et al. 2008).

Estimation of CBD and CBH fuel parameters

The CBD and CBH on all 50 plots located in the study area were estimated from a set of allometric equations and the CrownMass program in the FMAPlus 3 software (Fire Program Solutions/Acacia Services 2003).

Estimating canopy fuels using allometric equations

Crown bulk density (CrBD) is defined as the available biomass of the crown per unit volume of crown space (Cruz et al. 2003; Reinhardt et al. 2006). CrBD was calculated by dividing predicted forest foliage biomass by predicted crown volume for loblolly pines (Riaño et al. 2003) as follows:

\[ CrBD = \frac{FB}{CV} \]

where FB and CV are the tree’s foliage biomass and crown volume, respectively.

Jenkins et al. (2003) developed equations for predicting total aboveground biomass (eq. 2) and foliage biomass (eq. 3) for loblolly pine trees. The DBH was used in all the equations to estimate aboveground and tree component biomass. Their foliage biomass equation includes only the foliage component. The equations are

\[ B_{m} = \exp(\beta_{0} + \beta_{1} \ln(DBH)) \]

where Bm is total aboveground biomass (kilograms) for trees 2.5 cmDBH and larger, DBH is diameter at breast height (centimetres), exp is the exponential function, \( \beta_{0} \) is set to –2.5356, and \( \beta_{1} \) is set to 2.4349 and

\[ F_{bratio} = \exp\left(\beta_{0} + \frac{\beta_{1}}{DBH}\right) \]

where FBRatio is foliage biomass ratio to total aboveground biomass for trees 2.5 cm DBH and larger, \( \beta_{0} \) is equal to –2.9584, and \( \beta_{1} \) is equal to 4.4766.

As mentioned before, crown shape is the key to calculating crown volume. Baldwin and Peterson (1997) developed a crown model that considers both inner and outer shapes to predict the crown shape of loblolly pine forests, shown in Fig. 2. This is noteworthy because the inner shape was not considered in previous studies. In their study, they assumed that the profile is a simple balanced vertical cross sectional that involves outer and inner profile functions. A second-degree polynomial was used to model outer profile and the crown tip was set to zero. A straight-line model was used for inner defoliated cone-shaped area of the tree. Using their models and equations, maximum crown radius and its height, crown volume, and crown surface area can be determined. Their model can approximate a cone-shape crown. The crown volume equation they developed specifically for loblolly pine trees is given by

\[ V = \frac{1}{2} \pi \left( R_{1} + R_{2}\right) h \]

where \( R_{1} \) and \( R_{2} \) are the inner and outer radii, respectively, and \( h \) is the crown height.
The quantities $b_1$ through $b_4$ are defined by submodels:

\[ b_1 = -4.5121 + 0.5176\text{DBH} + 4.3529R \]
\[ b_2 = 4.4749 - 0.0175A - 0.4985\text{DBH} - 6.0414R \]
\[ b_3 = 0.0168\text{DBH} + 0.0155\text{FL} \]
\[ b_4 = -0.0233\text{DBH} \]

where $A$, $R$, and FL are the tree’s age, crown ratio, and foliated crown length, respectively.

In eq. 4, foliated crown length was calculated as total tree height minus CrBH obtained from the field data. Crown ratio was calculated as the ratio of crown length to total tree length. Site index and height information are needed to determine the age of a tree, necessary for eq. 4. Stukey (2009) developed eq. 5 to determine the age for the loblolly pine trees in our study area at base age 25:

\[ A = e^{\left[\frac{\text{TH} + 0.15A + \text{SI}}{0.617}\right]} \]

where TH is tree height and SI is site index.

Site index is described as the average height of the domi-
nant and codominant trees on the site at a given base age (Avery and Burkhart 1983). Site index for our study area was obtained from Soil Survey Geographic (SSURGO) data. The study area has site indices of 15.2 m (50 ft), 21.3 m (70 ft), 24.4 m (80 ft), 25.6 m (84 ft), and 27.4 m (90 ft) at 25 years.

By applying eq. 1, we obtained only CrBD at tree level, not the CBD at stand level. Henceforth, CBD estimated from allometric equations is named as CBD_{AL}. The CBD_{AL} was calculated as

$$\text{CBD}_{AL} = \frac{\sum FB}{\sum CV}$$

Lorey’s mean height, also called the weighted mean height approach, was used to calculate CBH in this study. This is a commonly used method in the United States. In our study, tree CrBH value was multiplied by tree basal area for all trees within the plot boundaries and then divided by the basal area of the stand (eq. 7). This method weights the contribution of trees to the stand height by their basal area by allowing the bigger trees to contribute more to the mean (Philip 2002). Because of the silvicultural treatments, e.g., thinning from below, harvesting smaller trees, and mortality of trees, Lorey’s mean approach is more stable than an unweighted mean approach (Brack 1999). As such, CBH estimated from Lorey’s mean height equation is named as CBH_{LH} and was calculated as

$$\text{CBH}_{LH} = \frac{\sum (BA \times \text{CrBH})}{\sum BA}$$

where CBH_{LH} is canopy base height estimated using Lorey’s mean height equation at the plot level, CrBH is crown base height at the individual tree level, and BA is basal area.

### Estimating CBD and CBH using the CrownMass program

For comparative purposes, CBD and CBH were also calculated using the CrownMass program within FMAPlus 3 software (Fire Program Solutions/Acacia Services 2003). The equations used in the CrownMass program are based on the work of Rothermel (1972), Andrews (1986), Finney (1998), and Beukema et al. (1999). Within CrownMass, crown mass prediction equations have been included for trees where published relationships are available. The program accepts and processes overstory data and estimates fire behavior and fire effects. Required inputs are tree DBH, tree height, tree crown ratio, trees per acre, tree species, fuel moisture, and tree structural stage. We obtained all required data from our field data. To estimate CBD and CBH canopy fuel parameters, each plot’s data were entered into the program by the authors and specialists from Texas Forest Service personnel involved with fire behavior and mitigation efforts in a joint meeting. Based on the tree list data, the software determines the canopy fuel loading for the needle and the 1 h time lag live/dead fuel categories. The program calculates the CBD and CBH canopy fuel parameters for different species types. First, the program estimates the number of trees per acre. The CBD is set as the maximum of the 1 ft (0.3048 m) layer running mean bulk densities. The CrownMass program also calculates crown load, foliage load, and tree load information to estimate CBD. The CrownMass program assumes that the distribution of crown loading is vertically uniform within the tree crown, which is assumed to be circular when viewed from above. Each tree is divided into 1 ft vertical segments from the tree’s CrBH to the tree’s total height by the program FMAPlus 3 (Fire Program Solutions/Acacia Services 2003). The loading for each 1 ft segment is calculated by summing the loading contributions to that segment from all trees within the stand. A running mean of these values is calculated and the maximum running mean value is used by this software as CBD (Fire Program Solutions/Acacia Services 2003). The CBH is determined by CrownMass as the lowest segment where the running mean segment bulk density is greater than the minimum crown bulk density, 0.0111 kg/m³. We will refer to the CrownMass estimators of CBD and CBH as CBD_{CM} and CBH_{CM}, respectively.

### Results

The allometric equations always produced higher values for average CBD (Fig. 5) and CBH (Fig. 6). The comparison of calculated general statistics for canopy fuel parameters is presented in Table 1.

The CBD values calculated using the allometric equations method varied between 0.03 kg/m³ (minimum) and 0.47 kg/m³ (maximum) with an average of 0.18 kg/m³. In comparison, CBD values obtained from the CrownMass program ranged between 0.006 kg/m³ (minimum) and 0.18 kg/m³ (maximum) with an average of 0.07 kg/m³. The average difference between the two methods is 0.11 kg/m³ and using allometric equations results in a value approximately 2.5 times greater than the value estimated by the CrownMass program. The CBD estimates from our method exceeded CrownMass program estimates by 157%. The distribution of average CBD values obtained from the two different methods is presented in Fig. 5.

The height values of CBH obtained from Lorey’s weighted height varied between 0.1 m (minimum) and 24.3 m (maximum) with an average height of 10.6 m. The height values of CBH obtained from the CrownMass program varied between 0.21 m (minimum) and 23.1 m (maximum) with an average height of 9.1 m. For CBH, Lorey’s weighted height estimates exceeded CrownMass program estimates by 16%. The distribution of average CBH values obtained from the two different methods is presented in Fig. 6.

### Discussion

For CBD estimates, our allometric equation results were higher than the CrownMass program CBD results. In our study, crown volume was calculated by considering only the space occupied by the canopy fuels and therefore generated results with higher CBD values over the entire study area. In previous studies, crown volume was overestimated by considering both space occupied and space not occupied by the canopy fuels in the tree crown (Keane et al. 2000; Cruz et al. 2003; Riaño et al. 2003). However, in this study, crown volume was calculated considering only the space occupied by the canopy fuels and the shape of the loblolly pine tree crowns. Therefore, comparatively low crown volume values were obtained. Further, dividing the foliage biomass by a smaller crown volume resulted in higher CBD values.
Brown (1978), 0.05 kg/m$^3$ from Fule et al. (2001), and CBD values were obtained in 1996 (2003). In addition to the results from 1870, the following 0.23 kg/m$^3$ from Cruz et al. (2003). Finally, in 2003, CBD was 0.03 kg/m$^3$ from Cruz et al. (2003). Roccaforte et al. (2008) concluded that for the same data set and area, average CBD for given this study is described in Brown (1978), Fule et al. (2001), and Cruz et al. (2003). The recent study by Roccaforte et al. (2008) compared three different methods of calculating the CBD canopy fuel parameter for three different years over the same study area: 1870, 1996–1997, and 2003. The CBD parameter used in this study was described in Brown (1978), Fule et al. (2001), and Cruz et al. (2003). Roccaforte et al. (2008) concluded that for the same data set and area, average CBD for given areas in 1870 was 0.02 kg/m$^3$ from Brown (1978), 0.01 kg/m$^3$ from Fule et al. (2001), and 0.03 kg/m$^3$ from Cruz et al. (2003). In addition to the results from 1870, the following CBD values were obtained in 1996–1997: 0.12 kg/m$^3$ from Brown (1978), 0.05 kg/m$^3$ from Fule et al. (2001), and 0.23 kg/m$^3$ from Cruz et al. (2003). Finally, in 2003, CBD was 0.05 kg/m$^3$ 0.13 kg/m$^3$ from Brown (1978), from Fule et al. (2001), and 0.22 kg/m$^3$ from Cruz et al. (2003). Brown’s (1978) estimates exceeded those of Fule et al. (2001) by 184%–268% and estimates of Cruz et al. (2003) exceeded Fule et al.’s (2001) estimates by 153%–491%. For the same area and the same data set, Scott (2008) ran two different canopy fuel calculation software, FuelCalc and FMAPlus. The differences between these two softwares were larger than they expected. Based on their conclusion, FMAPlus is overpredicting the canopy fuels compared with FuelCalc software. Therefore, CBD values obtained from allometric equations do not seem unreasonably high. Lorey’s mean height approach is one of the most accurate ways of calculating CBH without using any program because the average height and (or) the lowest CrBH will not repre- sent the stand as a whole. The average height results obtained from two different methods are quite close to each other and our estimation is 1.16 times more than that estimated by the CrownMass program. We also measured how these two methods are associated; therefore, the correlations between both methods were calculated for CBD and CBH in this study. There is a positive correlation between results of the two CBD methods CBD$_{CM}$ and CBD$_{AL}$, equal to 0.71. In addition, a strong correlation is found between the results of the two CBH methods CBH$_{CM}$ and CBH$_{AL}$, equal to 0.94. Conclusions When a wildfire burns out of control, the size of the losses can be almost inestimable. Improving the accuracy of mapping fuel loads is essential for fuel management decisions and for explicit fire behavior prediction for real-time support of suppression tactics and logistics decisions. Fire managers need more accurate fire behavior predictions, and benefits can be gained from improving key canopy fuel parameters such as canopy height, CBD, and CBH (Pyne et al. 1996).

The objective of this study was to improve and incorporate suitable allometric equations to estimate CBH and CBD canopy fuel parameters at the stand level, specifically for loblolly pine plantations. The CrownMass program was also used to estimate the same parameters as those produced from our calculations. In this way, we were able to assess our results. The results of this study show that our approach has great potential for becoming a standard method for estimating CBD and CBH canopy fuel parameters for loblolly pine trees in eastern Texas. Our values compared reasonably well with the CrownMass program estimates and yet highlight the differences due to adopted definitions of biomass and crown volume. Our results also highlight that considera- tion of crown shape is an important aspect when defining crown volume and CBD, a key canopy fuel parameter.

A digital elevation model, slope, aspect, surface fuel map, CBH, and CBD are required to run FARSITE. Many fire managers do not have the surface fuel map, CBD, or CBH data layers. Instead, they are required to use very coarse esti- mates of these inputs. There has been no reliable, accurate, and simple method for estimating these parameters and thereby providing high-quality input for FARSITE crown fire modeling. The same problem exists with regard to inputs for other fire simulation software packages such as Behave-Plus and FlamMap. It is imperative that these data sets be de- delivered in formats suitable for input to fire simulation systems used by fire managers. In addition, satellite remote sensing
technology has been proven to estimate forest inventory data over large areas (Ranson et al. 1997; Riaño et al. 2003). Previously, the estimation of canopy fuel parameters and the generation of canopy fuel maps from remote sensing required ground inventory data. Estimators CBD_{DL} and CBD_{HM} can be used as ground inventory data to estimates these parameters from remote sensing technology and then spatial explicit maps can be easily generated.

This study also highlights that canopy fuel parameters CBD and CBH can be easily derived using allometric equations. There is no published study on calculating CBD for this area. Fire managers can use our approach for loblolly pine trees in eastern Texas and they do not need to purchase any software such as FuelCal and (or) CrownMass to derive these parameters.

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References


