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Estimating canopy fuel characteristics for predicting crown fire potential in common forest types of the Atlantic Coastal Plain, USA

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Abstract. We computed four stand-level canopy stratum variables important for crown fire modelling – canopy cover, stand height, canopy base height and canopy bulk density – from forest inventory data. We modelled the relationship between the canopy variables and a set of common inventory parameters – site index, stem density, basal area, stand age or stand height – and number of prescribed burns. We used a logistic model to estimate canopy cover, a linear model to estimate the other canopy variables, and the information theoretic approach for model selection. Coefficients of determination across five forest groups were 0.72–0.91 for stand height, 0.36–0.83 for canopy base height, 0.39–0.80 for canopy cover, and 0.63–0.78 for canopy bulk density. We assessed crown fire potential (1) for several sets of environmental conditions in all seasons, and (2) with increasing age, density and number of prescribed burns using our modelled canopy bulk density and canopy base height variables and local weather data to populate the Crown Fire Initiation and Spread model. Results indicated that passive crown fire is possible in any season in Atlantic coastal plain pine stands with heavy surface fuel loads and active crown fire is most probable in infrequently burned, dense stands at low fuel moistures.

Additional keywords: allometric equations, canopy base height, canopy bulk density, CFIS, loblolly pine, longleaf pine.

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Introduction

Crown fires (CFs, Table 1) are uncommon in most forest types of the Atlantic coastal plain of the United States, but they can occur in any forest type given the right combination of surface and canopy fuel mass and structure, fuel moisture, wind speed and slope (Van Wagner 1977; Agca *et al.* 2011). In the south-eastern coastal plain, CF can occur during drought conditions (Oosting 1944; Marshall *et al.* 2008), especially in stands without prescribed fire for 5 or more years (Bickford and Bull 1935; Eldredge 1935; Outcalt and Wade 2004), which generally increases surface fuel loads. Observations of CF in the south-eastern US during drought conditions include the Hidden Pines Fire in Bastrop County, TX (Jackson 2016), Highway 31 Fire near Myrtle Beach, SC (South Carolina Forestry Commission 2010), and the Waldo Fire in Alachua County, FL (Florida Department of Community Affairs 2004).

The frequency and magnitude of drought appear to be increasing in the southern US (Mitchell *et al.* 2014; Clark *et al.* 2016), which may cause fires to burn more intensely and spread into tree crowns more frequently. Fires may also occur in forest types in which CF is unexpected; for example, during the 2016 Dick's Creek Fire in North Carolina, an active CF unexpectedly developed in a hardwood forest (USDA Forest Service 2016). If the climate continues to warm, wildfire conditions may worsen as indicated by predictions of longer fire seasons (Jolly *et al.* 2015) and increased fire potentials for the southern US (Liu *et al.* 2013; Mitchell *et al.* 2014). More specific predictions include (1) decreased precipitation along the Atlantic coastal plain of South Carolina, Georgia and Florida during the spring and increased Keetch–Byram Drought Index by late spring (Bedel *et al.* 2013); (2) an increase in average very large fire (VLF) potential and temporal increase in VLF potential for the south-eastern coastal plain (Barbero *et al.* 2015); and (3) an increase in cloud-to-ground lightning strikes with increased CO_2 in the atmosphere (Price and Rind 1994). Considering these predictions for the south-eastern US, better characterisation of surface and canopy fuels is needed to assess the potential for high-intensity CFs. Canopy characteristic and CF prediction work have been conducted in western US conifer forests (e.g. Cruz *et al.* 2003; Reinhardt *et al.* 2006) and the eastern US for pitch pine (*Pinus rigida* Mill.; Duveneck and Patterson 2007), loblolly pine (*Pinus taeda* L.; Mutlu 2010; Agca *et al.* 2011), and southern pine and hardwood forests (Wang *et al.* 2016), but to date, no characterisation of canopy

Table 1. List of frequently used abbreviations and their definitions

Abbreviation	Definition
AICc	Akaike's information criteria: a statistic used to measure goodness-of-fit for a model
AW	Akaike's weight: proportional representation of the fit of one regression model compared with the fits of all other candidate models
BA	Basal area ($m^2 ha^{-1}$): the cross-sectional area of all stems in a stand measured at breast height
CBD	Canopy bulk density ($kg m^{-3}$): the mass of available canopy fuel per unit canopy volume. This is a bulk property of the plot
CBH	Canopy base height (m): the lowest height above the ground above which there are sufficient canopy fuels to propagate fire vertically. Average of crown base heights, measured on the bole at the point the lowest live branch is attached. This is a bulk property of the plot
CC	Canopy cover proportion (%): the sum of the downward projection area of all dominant and codominant tree crowns relative to total area; expressed as a percentage
CF	Crown fire: a wildland fire that burns forest canopy fuel
DBH	Diameter at breast height (cm): diameter of tree measured 1.3 m above the ground
EFFM	Estimated fine fuel moisture: required input for Crown Fire Initiation System occurrence model. Calculated in the model using inputs for air temperature, relative humidity, month, hemisphere, time of day, slope, aspect and percentage shading
IT	Information theoretic approach: method for regression model selection
NB	Number of burns (no.): number of prescribed burns conducted on plot since stand establishment
SA	Stand age (years): estimated average age of stand based on tree cores from two to eight dominant or codominant trees within the plot
SD	Stand density (no. ha^{-1}): number of trees per unit area
SH	Stand height (m): average height of trees in the stand; estimated by averaging the heights of all 'in'-prism sampled trees
SI	Site index (m): estimated average height of the dominant and codominant trees at base age 50
SRS	Savannah River Site: US Department of Energy facility and National Environmental Research Park located in Aiken, South Carolina

fuels and CF potential has been conducted in the fire-prone southern Atlantic coastal plain.

Given the importance of understanding and predicting CF occurrence in the Atlantic coastal plain, obtaining estimates of canopy fuel stratum variables from available inventory measurements is essential. The estimates are effective for identifying stand characteristics and thresholds critical to CF ignition and spread. They can be used to parameterise landscape models of fire behaviour with local data and to illustrate how those parameters change over time. Our objectives were to (1) develop predictive equations for canopy characteristics important for CF modelling using available inventory data for five forest groups; (2) assess CF initiation likelihood using the Crown Fire Initiation and Spread (CFIS) occurrence model (Cruz *et al.* 2004; Alexander *et al.* 2006) under average fuel conditions and a range of seasonal weather scenarios; and (3) compare CF initiation and spread thresholds in forests of increasing age, density and number of burns. For the fire modelling objectives, we focused on loblolly pine because it is the most widespread forest type on our study site and is extensively planted in the south-eastern US and internationally.

Materials and methods

Study area and data

The study was conducted at the Savannah River Site (SRS), an 80 000-ha US Department of Energy facility and National Environmental Research Park located near Aiken, South Carolina (+33°20′39.84″, −81°44′28.32″). Forestland on SRS consists of pine-dominated forests, mixed pine–hardwood forests, mixed hardwoods and cypress–tupelo (*Taxodium distichum* (L.) Rich.–*Nyssa aquatica* L.) forests (Kilgo and Blake 2005). These forest types are typical of the upper coastal plain sandhills physiographic province of the south-eastern US. (Fig. 1). The five major forest types of SRS were sampled for the present study: pine plantations of loblolly, longleaf (*Pinus palustris* Mill.) or slash pines (*P. elliottii* Engelm. var. *elliottii*), mixed pine–hardwood forest, and bottomland hardwood forest.

Inventory data were collected in 1999 on permanent plots that were originally established in 1984–86 by USDA Forest Service Southern Research Station Forest Inventory and Analysis personnel. The plots are arranged on a 1000 × 1000-m grid across the forested areas of SRS, resulting in 629 plots (Parresol *et al.* 2012). Each plot was placed within a stand of the same forest type and age and consisted of a cluster of five subplots spaced 21.3 m apart. A variable-radius prism with an 8.61 basal area factor ($m^2 ha^{-1}$) was used for sampling overstorey trees and samples from the five subplots were combined. Subplot individual tree measurements included total height, height to the base of the live crown, diameter at breast height (DBH; measured 1.3 m above ground), tree canopy position (dominant, codominant, intermediate, or suppressed) and species for all prism sampled trees. Stand density (SD) and basal area (BA) were computed for each plot. Stand age (SA) at DBH was determined from tree cores for two to eight apparently undamaged dominant or codominant trees within the five subplots. Site index (SI) was calculated from the heights and ages of the dominant and codominant trees (Parresol *et al.* 2017). The number of prescribed burns since stand establishment (NB) in each plot was determined from a spatial database maintained by US Forest Service (USFS) – Savannah River that includes the year and location of prescribed fires conducted on SRS (Table 1).

From the inventory data, we calculated four canopy variables including canopy cover proportion (CC), stand height (SH), canopy base height (CBH) and canopy bulk density (CBD) (Table 2). These variables are commonly used to estimate CF initiation and spread potential in fire behaviour models (e.g. Fuel Characteristic Classification System (FCCS) (Prichard *et al.* 2013), Behave (Heinsch and Andrews 2010), and

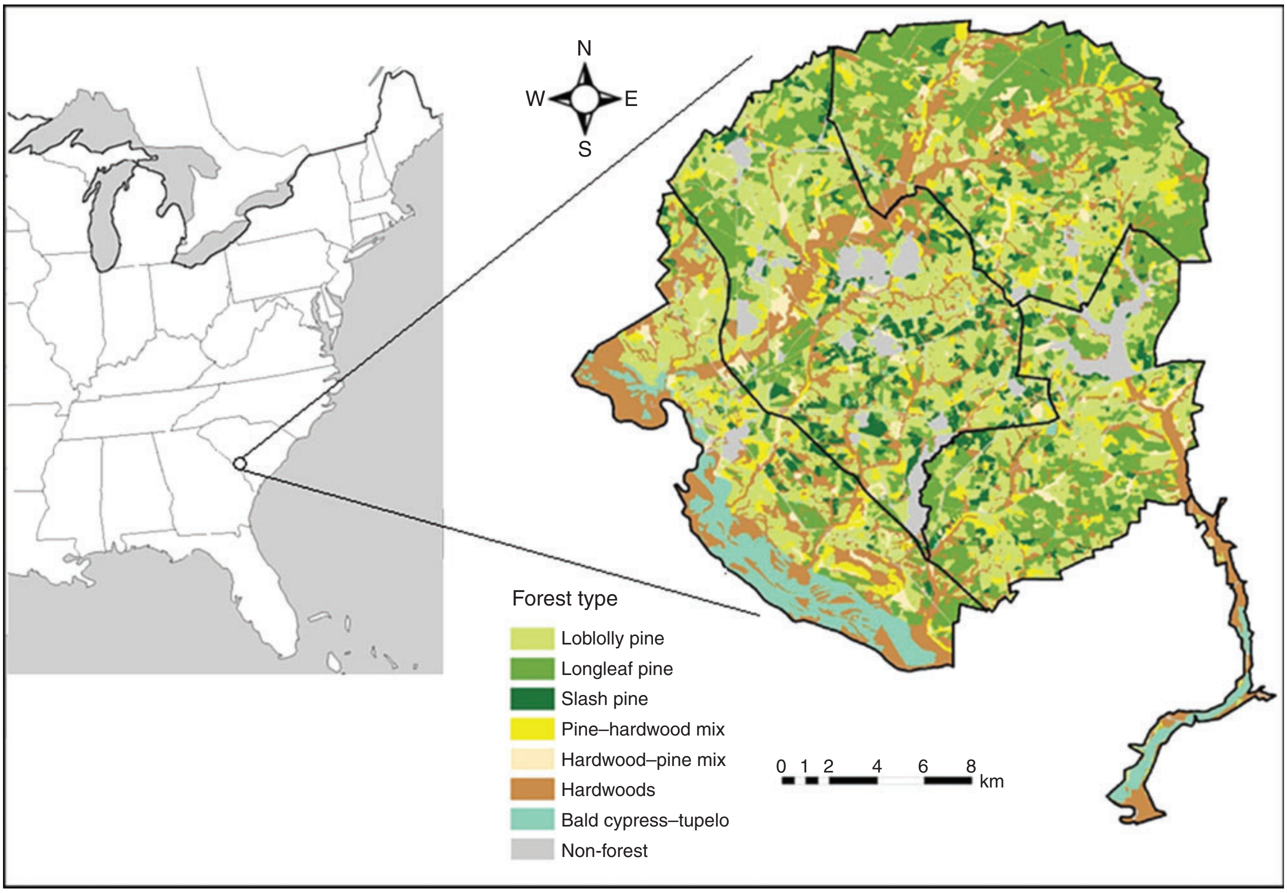

Fig. 1. Savannah River Site location in South Carolina, USA, with inventory locations and forest types.

Table 2. Summary statistics for five broad forest groups
Statistics including mean, median, standard deviation (s.d.), minimum value (Min) and maximum value (Max) for the variables canopy cover proportion (CC), stand height (SH), canopy base height (CBH) and canopy bulk density (CBD) at Savannah River Site

Forest group	Variable	Median	Mean	s.d.	Min	Max
Loblolly pine ($n = 269$)	CC	0.57	0.58	0.18	0.12	1.0
	SH (m)	21.14	20.27	7.30	3.31	36.79
	CBH (m)	9.60	9.74	5.05	0.30	23.77
	CBD (kg m^{-3})	0.111	0.130	0.083	0.019	0.809
Longleaf pine ($n = 129$)	CC	0.48	0.54	0.23	0.06	1.0
	SH (m)	20.81	18.07	7.41	2.74	28.35
	CBH (m)	9.14	8.50	4.94	0.30	16.76
	CBD (kg m^{-3})	0.084	0.102	0.070	0.005	0.424
Slash pine ($n = 56$)	CC	0.44	0.44	0.10	0.17	0.68
	SH (m)	25.24	25.09	2.30	17.02	29.67
	CBH (m)	12.57	11.62	4.48	2.13	18.75
	CBD (kg m^{-3})	0.096	0.097	0.031	0.035	0.171
Mix pine–hardwoods ($n = 71$)	CC	0.5	0.52	0.18	0.05	1.0
	SH (m)	21.42	20.92	6.27	5.64	34.29
	CBH (m)	6.55	7.34	3.84	0.91	16.00
	CBD (kg m^{-3})	0.056	0.062	0.032	0.013	0.230
Bottomland hardwoods ($n = 78$)	CC	0.56	0.56	0.15	0.26	1.0
	SH (m)	26.82	25.79	5.21	8.69	35.24
	CBH (m)	9.60	9.53	3.48	0.91	16.46
	CBD (kg m^{-3})	0.053	0.054	0.018	0.017	0.128

Table 3. Basic inventory plot variable statistics by broad forest group

Plot variables were used to predict canopy fuel variables. Summary statistics include median, mean, standard deviation (s.d.), minimum value (Min) and maximum value (Max) for stand age (SA), site index (SI) at 50 years, basal area (BA), stem density (SD) and number of prescribed burns since establishment (NB)

Forest group	Variable	Median	Mean	s.d.	Min	Max
Loblolly pine ($n = 269$)	SA (years)	34.0	33.2	17.5	4.0	90.0
	SI (m)	28.5	28.6	4.5	18.1	44.1
	BA ($m^2 ha^{-1}$)	24.9	25.1	8.7	1.5	50.2
	SD (no. ha^{-1})	502.3	817.3	724.1	26.3	3854.8
	NB (no.)	1.00	1.41	1.25	0.00	5.00
Longleaf pine ($n = 129$)	SA (years)	41.0	38.7	19.3	1.0	88.0
	SI (m)	26.2	26.0	5.1	15.3	36.9
	BA ($m^2 ha^{-1}$)	15.5	16.6	8.9	1.2	48.7
	SD (no. ha^{-1})	369.5	623.9	608.9	9.8	2596.9
	NB (no.)	2.00	1.84	1.16	0.00	5.00
Slash pine ($n = 56$)	SA (years)	44.0	44.5	4.6	31.0	62.0
	SI (m)	26.7	26.5	2.2	18.6	31.7
	BA ($m^2 ha^{-1}$)	23.5	24.5	7.5	9.5	41.0
	SD (no. ha^{-1})	327.3	388.9	209.0	108.0	1039.2
	NB (no.)	2.00	1.61	0.91	0.00	4.00
Mixed pine–hardwoods ($n = 71$)	SA (years)	52.0	49.7	15.6	2.0	80.0
	SI (m)	24.3	24.3	4.9	13.8	35.4
	BA ($m^2 ha^{-1}$)	21.4	21.0	8.4	3.0	43.2
	SD (no. ha^{-1})	313.7	492.3	412.5	48.5	1832.4
	NB (no.)	1.00	1.39	1.21	0.00	4.00
Bottomland hardwoods ($n = 78$)	SA (years)	57.0	57.3	16.8	16.0	95.0
	SI (m)	27.8	28.0	3.7	19.1	40.2
	BA ($m^2 ha^{-1}$)	28.7	29.1	9.9	2.1	54.8
	SD (no. ha^{-1})	333.8	405.5	348.0	87.6	2050.4
	NB (no.)	0.00	0.68	0.86	0.00	3.00

CFIS (Alexander *et al.* 2006)) and landscape fire models (e.g. FARSITE (Finney 2004) and FlamMap (Finney 2006)). Some of these canopy variables can be difficult to measure or estimate in the field. To facilitate their estimation, we modelled the relationship between the canopy variables and a set of common inventory parameters – SI, SD, BA, and SA or SH. As fire history can affect crown characteristics, number of burns (NB) was also included as an independent variable. Inventory plots were grouped into the five forest types (Table 3). We used a logistic model to estimate CC, linear models to estimate SH, CBH and CBD, and followed the information theoretic (IT) approach for model selection (Burnham and Anderson 2002).

Canopy cover proportion

We defined CC as the sum of the downward projection area of all dominant and codominant tree crowns relative to total area (McElhinny *et al.* 2005). For each prism sample, we used eqn 5, table 3 in Bechtold (2003) to determine crown diameter as a function of DBH and crown ratio for each species and converted crown diameter to projected area. If parameter estimates were not listed for a particular species, we applied the estimates of the most similar species based on tree form. We then used the standard formula to calculate a tree factor (TF_{ij}) for each tree from DBH, the basal area factor of the prism, and the number of subplots to convert prism sample data to unit area data (Kershaw *et al.* 2016).

An estimate of a per-unit-area characteristic of CC, X_i for each subplot i is

$$X_i = \sum_{j=1}^{m_i} TF_{ij} X_{ij} \tag{1}$$

where X_{ij} is the individual tree crown area projection for tree j on subplot i and m_i is the number of trees on subplot i.

The total unit area estimate of CC obtained from $n = 5$ subplots in a sample is obtained by dividing the sum of the subplot estimates by n and then dividing by the unit area, that is,

$$\mathrm{CC} = \frac{1}{5}\sum_{1=1}^{5} X_i/10000 \tag{2}$$

To account for crown overlap and to asymptotically constrain the values between 0 and 1, we corrected CC according to Crookston and Stage (1999) by applying the Beer–Lambert exponential equation in the following form:

$$\text{Corrected CC} = 100\left(1 - e^{-0.01\mathrm{CC}}\right) \tag{3}$$

where corrected CC is the value constrained between 0 and 1 and CC is from Eqn 2. All analysis and results listing CC are corrected CC values.

Table 4. Crosswalk between national-scale estimator equations and Savannah River Site species

National equations used to estimate foliage biomass	Codes for Savannah River species
Pine equation[A] softwood foliage ratio[B]	110, 111, 121, 128, 131
Cedar or larch equation softwood foliage ratio	221, 222
Hard maple/oak/hickory/beech equation hardwood foliage ratio	400, 401, 402, 403, 405, 409, 531, 802, 806, 807, 808, 812, 813, 819, 820, 822, 824, 825, 827, 831, 835, 837, 840, 841
Mixed hardwood equation hardwood foliage ratio	391, 460, 461, 491, 521, 540, 544, 555, 591, 602, 611, 621, 650, 652, 653, 660, 680, 682, 691, 693, 694, 701, 711, 721, 722, 731, 760, 762, 901, 931, 999
Aspen, alder, cottonwood, or willow equation hardwood foliage ratio	920, 970, 971, 972, 975
Soft maple or birch equation hardwood foliage ratio	313, 316, 370, 373, 661
Woodland conifer and softwood equation softwood foliage ratio	60

[A]All species group equations are from table 4 in Jenkins *et al.* (2003).
[B]All foliage ratios are from table 6 in Jenkins *et al.* (2003).

Stand height and canopy base height

We calculated SH (Table 2) using the prism sample with BA-weighted heights of all dominant and codominant trees. Height weighted by BA (effectively Lorey's height) is obtained directly when using prism sample observations (Kershaw *et al.* 2016). CBH is the height to the base of the lowest live branch on the individual tree. This definition is the typical forest inventory method but may differ from others who use lowest dead branch, and therefore, it may overestimate CBH for a given condition. We computed the BA-weighted median CBH from all trees on the plot. Although other researchers (e.g. Fulé *et al.* 2004) use mean CBH, we use the median because it is a more stable parameter, unaffected by extreme values. The BA-weighted median CBH value is directly obtained from the prism point sample median and accurately captures the contribution of larger trees in the calculation of CBH (Agca *et al.* 2011).

Canopy bulk density

CBD is the mass per unit volume of available canopy fuel (Scott and Reinhardt 2001) and generally consists of foliage and fine twigs less than 6 mm in diameter (Scott and Reinhardt 2001; Keane *et al.* 2005). Foliage biomass for each tree can be estimated using either national estimators as a function of DBH (Jenkins *et al.* 2003) or species-specific equations based on DBH, height and crown ratio, or the ratio of crown length to total tree height, to estimate biomass using more local equations. We used national-scale estimators to obtain our CBD estimates (Table 4). See the supplementary material (available online) for a comparison of national-scale estimators and species-specific biomass equations. There are no published data on fine twig biomass ≤6 mm for southern pines or hardwoods. Fine twig biomass was estimated using fine twig to foliage ratios for hardwoods (Loomis and Roussopoulos 1978; Loomis and Blank 1981; Snell and Little 1983) and pines (Brown 1978; Freeman *et al.* 1982). We plotted the fine twig to foliage ratio as a function of DBH for each species in the twig to foliage ratio studies listed above (Fig. 2). The ratio between small twig (≤6 mm) and foliage biomass is fairly stable across a wide range of diameter classes within both hardwood and pine species. We ignored DBH effects and, although the ratio appears to be variable between species, we calculated an overall average pine fine twig to foliage biomass ratio to estimate fine twig biomass for all southern pine species (0.43) and an overall hardwood ratio for all hardwoods (0.48). We then calculated crown fuel biomass as foliage biomass multiplied by the ratio for either pine (0.43) or hardwood species (0.48) plus foliage biomass. From the individual tree crown fuel biomass values, we calculated the canopy biomass using the same expansion methods used for CC (see Eqns 1 and 2). We then calculated CBD by dividing canopy biomass by canopy depth (SH – CBH).

Statistical methods

A series of models was developed and evaluated using the IT approach (Burnham and Anderson 2002) for CC, SH, CBH and CBD for each forest group. The IT approach allows explicit comparison among multiple models based on the corrected Akaike's information criteria (AIC_c). Candidate models are ranked using the AIC_c to obtain corresponding Akaike's weights (AW). Preferred models are those with the largest AW, representing the relative likelihood of a model having the best fit with respect to others in the candidate pool. Because the sum of the AWs for a series of models is 1, inspection of the magnitude of the AW for a given model indicates the strength of that model compared with the others.

All statistical analyses were performed using *SAS 9.4* (SAS Institute 2011). Twenty-six outliers in the dataset (<5% of the data) were dropped from the analysis on inspection of the data for the following reasons: (1) plots lacked data necessary to calculate one or all of the core variables owing to stand age (no canopy present) or incomplete data collection; (2) plot species composition did not correspond to any of the five forest type groups, e.g. plots that fell in cypress–tupelo forest; and (3) density, BA or height values were extreme outliers.

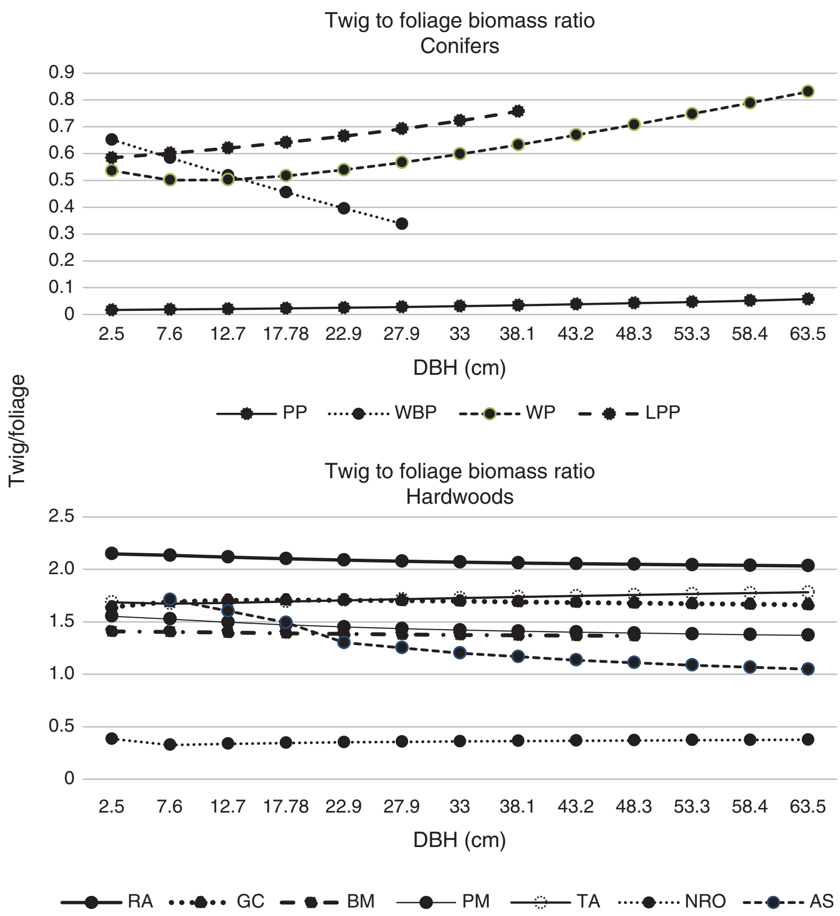

Fig. 2. Ratio of fine twig (≤6 mm) and foliage biomass for hardwoods and conifers. PP – ponderosa pine; WBP – white bark pine; WP – white pine; LPP – lodgepole pine (Brown 1978, table 16); RA – red alder; GC – giant chinkapin; BM – bigleaf maple; PM – Pacific madrone; TA – tanoak (Snell and Little 1983); NRO – northern red oak (Loomis and Blank 1981); AS – aspen (Loomis and Roussopoulos 1978).

A logistic equation was used for modelling CC to ensure that the dependent variable would be naturally bounded by zero and one:

$$CC = \left(1 + e^{bX}\right)^{-1} \tag{4}$$

where bX is the linear combination of the independent variables (SD, SA, BA, SI and NB).

Multiple linear models were used for the dependent variables SH, CBH and CBD as functions of the independent variables SD, BA, SI, NB and SA (or SH in the case of modelling CBH). Initially, we also tried a form of the non-linear Chapman–Richards model for these crown variables but ran into difficulties with non-convergence and problems with selecting initial starting values. As there were five species groups and four crown variables, each combination with numerous models to fit, it became too difficult to resolve all the problems that arose with fitting each model to the Chapman–Richards function.

We performed model selection for each dependent variable and forest group in two steps. Based on initial data analysis, previous inventory research and theoretical grounds, we determined *a priori* that SD was the most important driving independent variable for CC, SH, CBH and CBD, so we forced it into all models. Biologically, this is reasonable as SD is related to stand growth dynamics with regard to SH parameters via density-dependent mortality and residual thinning density; crown base height via spacing-crown ratio relationships; canopy cover via the direct effect of density on canopy cover; and similarly for CBD. In the first IT modelling step, we used the five main independent variables only (SD, BA, SI, SA or SH) and NB, resulting in 16 models for each dependent variable and forest group. Producing a larger number of models was unnecessary based on the dominant effect of SD. The models consisted of the baseline model with SD and all one-, two-, three- and four-variable combinations of BA, SI, SA or SH, and NB, but no interactions. The model with the best fit of this group based on largest AW was selected for use in the examination of all logical two-way interactions.

Each interaction model contained all variables from the best model and one of the two-way interactions. However, no interaction with NB was considered even if NB was in the best model. Interactions between NB and SA, SH, SI, BA or SD were

Table 5. Stand height (SH) model parameters, standard errors and fit statistics

Models predict stand height (m) as a function of plot variables for each broad forest group at Savannah River Site based on the information theoretic approach. Standard errors are in parentheses. SSE, sum of squared errors; AIC_c, Akaike's information criterion

Main variables	Coefficients for variables and interactions by forest group (s.e.)				
	Loblolly pine	Longleaf pine	Slash pine	Mixed pine–hardwood	Bottomland hardwoods
Intercept	1.5155 (1.2038)	−1.2115 (1.6765)	−1.3052 (2.7180)	−0.0262 (2.0277)	0.0282 (3.6499)
Stand age (years)	0.2882 (0.0136)	0.1855 (0.0235)	0.1975 (0.0360)	0.1584 (0.0225)	0.2442 (0.0489)
Site index (m, 50 years)	0.2831 (0.0324)	0.4609 (0.0493)	0.6759 (0.0765)	0.5513 (0.0600)	0.3346 (0.0866)
Stand density (stems ha^{-1})	−0.0009 (0.0004)	−0.0056 (0.0005)	−0.0033 (0.0008)	−0.0062 (0.0007)	−0.0067 (0.0009)
Basal area ($m^2\,ha^{-1}$)	0.1860 (0.0175)	0.3749 (0.0650)	0.0396 (0.0224)	0.1309 (0.0395)	0.4841 (0.1045)
Number of burns	–	–	–	–	–
Interactions in best model					
Stand age × stand density	−0.0002 (0.00002)	–	–	–	–
Stand age × basal area	–	−0.0036 (0.0013)	–	–	−0.00518 (0.0017)
n (observations)	269	129	56	71	78
Fit statistics					
SSE	1189.36	769.22	74.59	247.99	446.53
AIC_c	412.18	243.03	27.25	99.72	149.28
Adjusted R^2	0.9151	0.8861	0.7246	0.9043	0.7714
Akaike's weight[A]	0.6550	0.5079	0.4655	0.7535	0.5238

[A]From information theoretic approach.

expected to be confounded with stand development as the number of burns intrinsically increases with SA and correlated variables. For SH prediction models, no interaction between SI and the other independent variables was considered for similar reasons. This procedure, designed to incorporate interactions between variables, resulted in a series of three to six interaction models that were compared with their associated best non-interaction model using AWs. This process resulted in the final model for each variable and forest group. At each stage, we inspected the model residuals for trends and the predicted vs observed for bias.

Crown Fire Initiation and Spread model methods

To evaluate the likelihood of CF in southern Atlantic coastal plain pine forests, we used the occurrence model within the CFIS system (Alexander *et al.* 2006). The occurrence model requires the following inputs: mean CBD, fuel stratum gap (FSG, which we calculated as mean CBH minus mean shrub height), 10-m wind speed (wind speed measured 10 m above the surrounding vegetation), surface fuel consumption class (SFC), and several site and weather conditions to calculate estimated fine fuel moisture (EFFM). A pine forest subset of 471 of the 629 plots sampled in 1999–2000 was used to determine mean shrub height for the calculation of FSG (Parresol *et al.* 2012). We used 10 years of SRS Remote Automated Weather Station (RAWS) data to determine wind speeds and EFFMs for each season – spring (March–May), summer (June–August), fall (autumn) (September–November) and winter (December–February). For EFFM calculations, we used the highest daily average sustained wind speed from each 3-month season and several air temperature and relative humidity values, recorded on the same day, from each 3-month span to create an array of reasonable potential EFFMs for each season. We held the following values constant in the EFFM calculator: month (middle month of season), hemisphere (Northern), time of day (1300–1500 hours), slope (<30%), aspect (south) and shading (>51%). To determine reasonable SFC classes for use in the model, we compiled data from several fuel consumption studies conducted on or near SRS. Prichard *et al.* (2014) report a maximum of shrub, herb, litter and woody fuel consumption of 1.57 kg m^{-2} on south-eastern coastal plain plots. Goodrick *et al.* (2010) report a mean fuel consumption of 0.72 kg m^{-2} with a range up to 1.93 kg m^{-2} during prescribed fires at SRS. Our plot surface fuel loadings ranged from 0.55 to 5.37 kg m^{-2}. Considering 77.9% mean consumption for the burn sites of Prichard *et al.* (2014), SFC > 2 kg m^{-2} is not unreasonable for some stands in our study area. Therefore, we ran the model with 1–2 kg m^{-2} and >2 kg m^{-2} consumption of surface fuels to capture potential greater consumption values during wildfire conditions. Because spring weather conditions produced the highest likelihood of CF in our previous CFIS runs, we used the CFIS occurrence model to assess the effect of NB (0, 3 and 5 burns) on CF initiation and spread in stands with varying SA (20, 30, 40 and 50 years) and SD (100, 300 and 900 trees ha^{-1}) under sets of observed spring weather conditions. CBH and CBD were calculated for each age–density pair using our allometric equations. Mean pine plot shrub heights in stands with 0, 3 and 5 burns were used to calculate FSG.

Results

Canopy fuel stratum variables

All SH final models included the basic inventory stand variables of SA, SI, SD and BA, and resulted in reasonable fits to the data for each group based on AWs (Table 5). SA and SI were positively related to SH and density was negatively related to SH. Loblolly pine, longleaf pine and the mixed pine–hardwoods had adjusted R^2 of 0.92, 0.89 and 0.90 respectively. Model fits for slash pine and bottomland hardwoods were weaker, with

Table 6. Canopy base height model parameters, standard errors and fit statistics
Models predict canopy base height (m) as a function of plot variables for each broad forest group at Savannah River Site based on the information theoretic approach. Standard errors are in parentheses. SSE, sum of squared errors; AIC_c, Akaike's information criterion.

Main variables	Coefficients for variables and interactions by forest group (s.e.)				
	Loblolly pine	Longleaf pine	Slash pine	Mixed pine–hardwood	Bottomland hardwoods
Intercept	−4.0590 (1.0377)	−5.8757 (1.2543)	74.3518 (34.7215)	3.5755 (4.8326)	−4.3276 (2.3210)
Stand height (m)	0.6324 (0.0375)	0.6359 (0.0517)	−2.2042 (1.4820)	−0.0017 (0.2397)	0.3419 (0.0810)
Site index (m, 50 years)	–	0.0849 (0.0395)	−3.2834 (1.3841)	−0.2474 (0.2048)	0.1294 (0.0665)
Stand density (stems ha^{-1})	0.0006 (0.0004)	0.0011 (0.0008)	−0.0066 (0.0026)	−0.000157 (0.0009)	−0.00202 (0.0009)
Basal area ($m^2 ha^{-1}$)	–	–	0.1430 (0.0686)	–	0.0772 (0.0319)
Number of burns	0.3329 (0.1282)	0.4065 (0.1607)	–	–	–
Interactions in best model					
Stand height × stand density	–	−0.00009 (0.00006)	–	–	–
Stand height × site index	–	–	0.1177 (0.0567)	0.01885 (0.0096)	–
n (observations)	269	129	56	71	78
Fit statistics					
SSE	1725.30	495.21	645.33	297.68	315.98
AIC_c	508.073	186.216	150.601	112.690	119.953
Adjusted R^2	0.7444	0.8348	0.3575	0.6948	0.6428
Akaike's weight[A]	0.47278	0.56945	0.20094	0.28896	0.35716

[A]From information theoretic approach.

adjusted R^2 of 0.72 and 0.77 respectively. For the best loblolly pine model, the addition of the SA × SD interaction term improved the model slightly. Similarly, for longleaf pine and bottomland hardwoods, the final model selection included the SA × BA interaction. Adding interactions did not improve the models for slash pine and mixed hardwoods.

Final model fits for CBH based on AWs varied more widely than for SH (Table 6). All models included SH and SD, four SI, and two BA. However, the models provided reasonable fit for the two dominant species on SRS, loblolly and longleaf pine. The best models for these two species had adjusted R^2 of 0.74 and 0.83 respectively and AWs of 0.47 and 0.57. The signs of the parameter coefficients were generally consistent in these two species and positive for SH, SD and NB. The NB was included in the best model for loblolly and longleaf pines, indicating that prescribed fires were an important variable contributing to the increase in CBH for these species. In contrast, fit statistics were lower for predicting CBH for slash pine, mixed pine–hardwood and bottomland hardwood groups. However, only slash pine fit statistics were poor, with an adjusted R^2 of 0.36 and an AW of 0.20. Interactions were important only for longleaf pine (SH × SD), slash pine (SH × SI), and mixed pine–hardwoods (SH × SI). Parameter estimates for SH and SI were negative in the slash and mixed pine–hardwood groups, but interaction terms were positive, suggesting relationships to CBH are complex.

Logistic model fits for CC of the pine species were reasonably good. Pseudo-R^2 (defined as 1 – (error sum of squares/total corrected sum of squares)) values ranged from 0.71 to 0.80 (Table 7). Canopy cover predictions for mixed pine–hardwoods and bottomland hardwoods were much weaker than for pine plantations. Measures of stocking, SD and BA, or their interaction term were the common variables in all models for the five forest groups. NB was not incorporated in the best model for any group. SA was only considered in mixed pine–hardwood models and SI was only included in loblolly pine and bottomland hardwoods models. Adding BA × SD interaction substantially improved fit and decreased bias in loblolly pine and mixed pine–hardwood models.

The best CBD models were fairly consistent across all forest groups, with adjusted R^2 values ranging from 0.66 to 0.77, but varied with respect to the AWs (Table 8). Stocking metrics of SD or BA, and interactions of SD × SA or SD × BA, were the dominant variables for all models. Site index was only included in the models for loblolly and longleaf pines and SA for loblolly pine and bottomland hardwoods. The CBD was always positively related to SD, BA, SI and SA. Similarly to results for SH and CC, NB was not an important variable contributing to the prediction of CBD in any forest group.

Crown Fire Initiation and Spread model results

The CFIS occurrence model was populated with a mix of inventory data and modelled values. Based on our modelled values of CBD and CBH, mean pine forest shrub height (to calculate FSG), and SRS RAWS temperature and relative humidity data, results indicate that winter and spring have a higher potential for CF than summer and fall on our study site (Table 9). The highest seasonal maximum wind speeds occurred during winter (14.6 km h^{-1}) and spring (14.2 km h^{-1}). Summer and fall maximum wind speeds were 11.2 and 12.3 km h^{-1} respectively. The combinations of temperature and humidity recorded during spring produced the lowest EFFM value (5), whereas the lowest EFFM value in both summer and fall was 6. The most severe combinations of weather variables during each season yielded 47–84% probability of passive CF in spring, 44–82% in winter, 25–67% in fall and 18–57% in summer. Predicted rates of spread were also were also lower for summer (13.6 m min^{-1}) and fall (14.3 m min^{-1}) than for winter (15.5 m min^{-1}) and spring (16.5 m min^{-1}).

Our investigation of the effects of NB on the likelihood of CF showed that prescribed burning reduced CF probability in all

Table 7. Canopy cover proportion model parameters, standard errors and fit statistics

Models predict canopy cover proportion as a function of plot variables for each broad forest group at Savannah River Site based on the information theoretic approach. Standard errors are in parentheses. SSE, sum of squared errors; AIC_c, Akaike's information criterion.

Main variables	Coefficients for variables and interactions by forest group (s.e.)				
	Loblolly pine	Longleaf pine	Slash pine	Mixed pine–hardwood	Bottomland hardwoods
Intercept	2.2048 (0.1940)	0.8050 (0.0795)	1.2216 (0.1319)	1.2412 (0.3921)	1.4323 (0.4842)
Stand age (years)	–	–	–	0.0140 (0.0055)	–
Site index (m, 50 years)	−0.0193 (0.00538)	–	–	–	−0.0237 (0.0159)
Stand density (stems ha^{-1})	−0.0021 (0.0001)	−0.00176 (0.0001)	0.00035 (0.0002)	−0.0028 (0.0006)	−0.0011 (0.0002)
Basal area ($m^2\,ha^{-1}$)	−0.0477 (0.00440)	–	−0.0452 (0.0044)	−0.0785 (0.0155)	−0.0207 (0.0057)
Number of burns	–	–	–	–	–
Interactions in best model					
Basal area × stand density	0.00004 (5.215×10^{-6})	–	–	0.0001 (0.00003)	–
Stand age × stand density	–	–	–	–	–
n (observations)	269	129	56	71	78
Fit statistics					
SSE	1.7294	1.84509	0.16736	1.03595	0.99196
AIC_c	−1347.40	−543.804	−319.063	−289.220	−331.90
Pseudo-R^2	0.79731	0.71803	0.70915	0.54377	0.39196
Akaike's weight[A]	0.46807	0.13697	0.42384	0.45717	0.19570

[A]From information theoretic approach.

Table 8. Canopy bulk density model parameters, standard errors and fit statistics

Models predict canopy bulk density ($kg\,m^{-3}$) of foliage from national-scale estimators and twigs (≤6 mm) as a function of plot variables for each broad forest group at Savannah River Site based on the information theoretic approach. Standard errors are in parentheses. SSE, sum of squared errors; AIC_c, Akaike's information criterion

Main variables	Coefficients for variables and interactions by forest group (s.e.)				
	Loblolly pine	Longleaf pine	Slash pine	Mixed pine–hardwood	Bottomland hardwood
Intercept	−0.0885 (0.0274)	−0.0528 (0.0188)	0.0132 (0.0096)	−0.0209 (0.0077)	0.0058 (0.0073)
Stand age (years)	0.0019 (0.00031)	–	–	–	0.00008 (0.00012)
Site index (m, 50 years)	0.0026 (0.0007)	0.0010 (0.0006)	–	–	–
Stand density (stems ha^{-1})	0.0001 (0.00001)	0.0002 (0.00001)	5.3169×10^{-7} (0.00001)	0.0001 (0.00001)	0.00006 (0.00001)
Basal area ($m^2\,ha^{-1}$)	–	0.0046 (0.0006)	0.0034 (0.0003)	0.0028 (0.0003)	0.0011 (0.0001)
Number of burns	–	–	–	–	–
Interactions in best model					
Stand age × stand density	−0.000002 (4.9826×10^{-7})	–	–	–	-6.3923×10^{-7} (1.9760×10^{-7})
Basal area × stand density	–	−0.000005 (6.8925×10^{-7})	–	−0.000004 (5.5651×10^{-7})	–
n (observations)	269	129	56	71	78
Fit statistics					
SSE	0.6204	0.1528	0.0164	0.0158	0.0084
AIC_c	−1623.19	−858.79	−449.16	−588.55	−701.43
Adjusted R^2	0.6578	0.7480	0.6730	0.7731	0.6612
Akaike's weight[A]	0.4397	0.2639	0.2532	0.3433	0.2735

[A]From information theoretic approach.

density and age classes; however, the effect of NBs was much lower in young stands than in older stands (Fig. 3). In addition, the dampening effect of higher EFFM is lower in young stands than in older stands. Our results also indicate that at the same EFFM, young, dense stands were more likely to experience CF than older stands. For example, at EFFM 5, a 20-year-old stand with 900 trees ha^{-1} has an 85% probability of CF and a 50-year-old stand with 900 trees ha^{-1} has only a 36% probability of CF. However, active CF was possible in dense stands in all age classes with moderate to heavy surface fuel loads and low fuel moistures (EFFM 5). Stands with the lowest potential for CF are older stands with higher CBH. For example, at EFFM 7,

Table 9. Input parameters and results from Crown Fire Initiation and Spread occurrence model for each season
EFFM, estimated fine fuel moisture; ROS, predicted crown fire rate of spread; SFC, surface fuel consumption class; CF, crown fire

Season	Wind speed (km h^{-1})	EFFM[A]	Temperature (°C)	Relative humidity (%)	Probability[B] (%) Fire type	Probability (%) Fire type	ROS (m min^{-1})
					SFC 1–2.0 kg m^{-2}	SFC > 2.0 kg m^{-2}	
Winter	14.6	7	11.1	9	44% Surface fire	82% Passive CF	15.5
		10	28.3	35	20% Surface fire	60% Passive CF	10.1
		11	10	42	16% Surface fire	53% Passive CF	8.9
Spring	14.2	5	26.7	8	47% Surface fire	84% Passive CF	16.5
		7	37.2	20	34% Surface fire	75% Passive CF	14.0
		9	25.3	39	22% Surface fire	63% Passive CF	11.2
		12	21.7	57	11% Surface fire	42% Surface fire	–
Summer	11.2	6	38.9	17	18% Surface fire	57% Passive CF	13.6
		7	42.2	21	14% Surface fire	50% Surface fire	–
Fall	12.3	6	18.9	12	25% Surface fire	67% Passive CF	14.3
		8	37.2	25	16% Surface fire	53% Passive CF	11.6

[A]In addition to temperature and humidity, other values used to calculate EFFM in all seasons were month (the middle month of each 3-month season), northern hemisphere, 1300–1500 hours time of day, <30% slope, south aspect, and >50% shading.
[B]Probability of crown fire occurrence (Cruz *et al.* 2004).

50-year-old stands with CBH ≥12.6 m have 0% CF probability and at EFFM 5, 50-year-old stands have only 12% probability of crown fire.

Discussion

Canopy fuel stratum variables

Results suggest that modelling SH, CC, CBH and CBD from basic forest inventory variables using national crown foliage biomass estimators provides a reasonable approach to estimate canopy fuel stratum variables across large spatial scales. Equations appear to have minimal bias and moderate precision, at least within a defined landscape such as SRS. Direct empirical measurement from destructive sampling to obtain canopy fuel data is prohibitively expensive and generally impractical for many managers and landowners. The data we used are similar to national Forest Inventory and Analysis program (FIA) inventory data that are collected periodically throughout the region (Bechtold and Patterson 2005). Modelling canopy fuel stratum variables in this manner using FIA data enables continuous canopy models of crown ignition potential to be developed in conjunction with either forest type maps or remotely sensed data, such as National Agriculture Imagery Program (NAIP) imagery (Dappen 2011). For example, Hulet *et al.* (2014) estimated tree cover and biomass using NAIP imagery to cost-effectively evaluate tree encroachment into sagebrush steppe vegetation. Although steppe is more open and less structurally diverse than south-eastern forests with multiple canopy layers, similar methods could potentially be used to estimate some canopy characteristics in forest systems.

We expect that similar statistical results in terms of bias and precision in model parameters would be found in other areas of the Atlantic coastal plain. Forest management at SRS is representative of a wide range of non-industrial private and state lands in the upper portion of the Atlantic coastal plain in terms of species, age and stocking conditions. However, SRS stands are not generally representative of intensively managed industrial lands in the region, which would have more uniform composition, size and age range (Siry 2002). The actual stand management regime, combined with the range of sampled conditions, limits generalisation of our equation parameters. Nevertheless, we expect the dominant stand variables, such as SD, and their relative importance to be similar across regions of the same forest types when estimating stand parameters.

Although management influences canopy fuel structures, most of our canopy variables fall with the range of natural and managed pine forests throughout the US. Our mean forest group CC values ranged from 44 to 58%; this range is narrower than photo series data for similar south-eastern forest types (Ottmar 2000; Ottmar *et al.* 2003), which range from 15 to 69% cover, but similar to that reported by Bried *et al.* (2015) in New Jersey pine barrens in the north Atlantic coastal plain (35–63% cover). CBH values at SRS ranged from 7.34 to 11.62 m. Similar values were reported by Mutlu (2010) in eastern Texas, Fulé *et al.* (2004) in Arizona, and Bried *et al.* (2015). Gill *et al.* (2000) studied a mix of western conifers in California and report a generally higher range of CBH values (9.2–20.2 m), whereas Cruz *et al.* (2003) found a lower range (4.5–6.1 m) in ponderosa pine (*Pinus ponderosa* Lawson and C. Lawson) and lodgepole pine (*Pinus contorta* Douglas ex Loudon) forests in five western states. Our CBD values ranged from 0.062 to 0.13 kg m^{-3} and were similar to those reported by Fulé *et al.* (2004) and Bried *et al.* (2015), but are somewhat lower than Cruz *et al.* 2003 and Scott and Reinhardt (2005), and much lower than CBD values reported by Brown (1978) for 11 western conifers.

A major challenge in the south-eastern US is the diversity of tree species and extent of mixed species stands. To model the data, we defined conditional populations as broad forest groups that, in reality, represent mixtures of species. For example, a mixed pine–hardwood stand could be loblolly pine and sweetgum or loblolly pine, slash pine and three oak species. Therefore, the precision of this forest group's equations is inherently low. The high tree species diversity may explain the more variable relationships (lower adjusted R^2 values) observed in CC, CBH and CBD, particularly for the bottomland hardwood forest group.

The lack of effect of the number of past burns on SH, CC and CBD is not surprising unless NB has a direct effect on stocking through mortality that is not compensated by regeneration. Zarnoch *et al.* (2014) found that the rates of snag formation (tree mortality) depended on the time since last burn and not the NB for loblolly pine. However, similar simple relationships were not observed for mixed-pine, hardwood or longleaf stands in that study. The NB is a logical variable for estimating effects on CBH because, unlike surface fuels that are constantly renewed through growth and litter fall, the crown base of these species cannot regenerate if it is killed by fire. Prescribed fire was a significant predictor variable in final CBH models for loblolly and longleaf pines. Both of these forest groups are routinely burned and fires in them burn more consistently and intensely owing to their continuous beds of pine litter. In contrast, the intensity and flame length in mixed pine–hardwood and hardwood stands are often much lower (Kreye *et al.* 2013). The CBH was less sensitive to change over the range of NB compared with the effects of stand development as represented by the range of SH. In general, mean CBH increases about 1 m following three prescribed fires in loblolly and slightly more in longleaf pine.

The relative stability of the fine twig to foliage biomass ratio within a species across a wide range of DBH has not been studied previously. Our analysis suggests that, where observations for individual species are lacking, such as in the Atlantic coastal plain region, using a single value across the range of DBH is not an unreasonable approximation. The variability between species means that using this method of approximation is unsuitable for inferring precise values for CBD. No published or unpublished values for any south-eastern US species could be found. Because our method depends on the calculated foliage biomass, error in the estimates of foliage biomass introduced by the choice of allometric equations can change the CBD values substantially.

Crown Fire Initiation and Spread model

Passive CF (torching) often occurs in isolated areas of large prescribed and wildfires where fuel load, arrangement and environmental conditions promote transition of the flaming front into crown fuels. Our CFIS results suggest that passive CF is possible in any season in forests with heavy surface fuel loading (≥ 2 kg m^{-2}) (Table 9). Owing to high site productivity, surface fuel loads in the south-eastern US accumulate rapidly in the absence of frequent fire (Brose and Wade 2002; Parresol *et al.* 2006). Depending on local site productivity, within 3–5 years since fire, live and dead surface fuel accumulations can reduce the space between surface fuels and CBH (or FSG), which increases the likelihood of CF initiation (Wang *et al.* 2016; Cruz *et al.* 2004). Although CFs are possible in any season, they are more likely to occur during the winter and spring based on our CFIS results (Table 9). These findings are consistent with South Carolina's wildfire season, which is from January through mid-April (South Carolina Forestry Commission 2018).

We used spring wildfire season weather conditions in the CFIS occurrence model to assess the effect of NBs in plots with increasing age and density on CF initiation and spread. With increased prescribed burning, fuel alterations reduced the likelihood of CF initiation. For example, in plots with 0 burns, mean surface fuel height was 1.47 m, whereas plots with three and five burns had mean shrub heights of only 0.75 and 0.52 m respectively. The decrease in shrub height, which increased the FSG, reduced the likelihood of CF development with increasing NB (Fig. 3). Our modelled results are similar to empirical results noted by Outcalt and Wade (2004) and Martinson and Omi (2008), who reported lower tree mortality and reduced fire behaviour after repeated prescribed burns respectively.

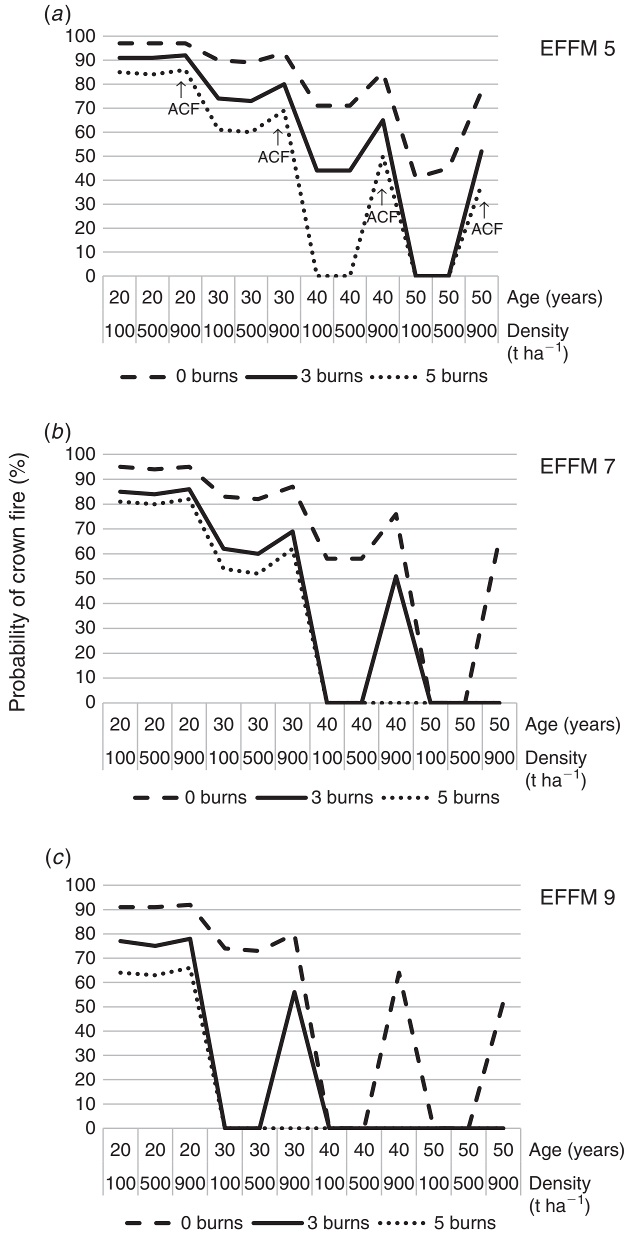

Fig. 3. Probability of crown fire in loblolly pine stands with increasing number of prescribed burns across a range of ages and densities. All values were calculated with the highest wind speed of the spring season and surface fuel consumption >2 kg m^{-2}. The top panel (*a*) was calculated at estimated fine fuel moisture (EFFM) 5; (*b*) was calculated at EFFM 7; and (*c*) was calculated at EFFM 9. In panel (*a*), ACF indicates potential for active crown fire.

Active CFs are uncommon in the Atlantic coastal plain, but do occur in this region. For example, in 2009, the Highway 31 fire in eastern South Carolina was intense enough to jump a major highway and destroy over 70 homes (South Carolina Forestry Commission 2010). Our CFIS results suggest that active CF is possible at any age, but is much more likely in younger stands regardless of prescribed fire activity. Additionally, active CFs are more probable in the densest stands at any age. However, even at very low fuel moisture (EFFM 5 in our study), older stands with repeated prescribed burns had lower probability of active CF, except in the densest stands (900 trees ha^{-1}), which also had the highest CBD (0.12 kg m^{-3}) (Fig. 3a). The generally accepted CBD threshold for active CF development is 0.1 kg m^{-3} (Agee 1996; Powell 2010; Alexander and Cruz 2011). In our study, active CF occurred at modelled CBD values of 0.12 kg m^{-3}, which suggests that our CF findings for south-eastern pine forests are not unreasonable. Stands with the lowest potential for CF are 50-year-old stands with low to moderate tree density and CBD but high CBH, indicating that thinning to reduce CBD or in some cases removing ladder fuels and pruning canopy trees to increase CBH may be sufficient to reduce CF potential (Keyes and Varner 2006). However, Keyes and Varner (2006) warn that following thinning, increased light may decrease fuel moisture and increase surface and future ladder fuel growth, which could exacerbate CF potential over time.

Active CFs can occur during extreme weather conditions, such as our EFFM 5 scenario, and may become more common under a warming climate (Mitchell *et al.* 2014). Fire potential ratings based on Keetch–Byram Drought Index are currently highest during winter and spring in the eastern part of the south-east, including South Carolina (Mitchell *et al.* 2014). Although precipitation forecasts are not consistent across climate models (Mitchell *et al.* 2014), evidence suggests that periods of concurrent droughts and heatwaves, which could produce extreme fire conditions, have increased significantly in the south-east US (Mazdiyasni and AghaKouchak 2015) and are likely to continue to increase in the future (Zscheischler and Seneviratne 2017). In addition, Liu *et al.* 2013 indicate fire seasons are expected to increase by one to three months in the south-east. The combination of longer fire seasons and more extreme fire weather conditions could increase the likelihood of CF in the south-east in the future and decrease the number of days available for prescribed burning to reduce surface fuel loads (Mitchell *et al.* 2014). Although various combinations of fuel reduction techniques are used in the south-east, prescribed fire is the most common. If climate scenarios are accurate, prescribed fire use will likely decrease and a move towards a creative combination of prescribed fire, mechanical and chemical fuel reduction techniques may become necessary to reduce fuel continuity and loading in the future.

Conclusions

Our canopy fuel equations and methods are applicable to similar pine and hardwood forests throughout the south-eastern US. However, validation and calibration of the estimates of CBD and CC are needed to establish the precision and possible bias that limit interpretation. Further, our methods can be applied to other areas by using national-scale biomass estimators and local FIA data, facilitating the estimation of CF potential over large spatial scales.

The CFIS model results illustrate that reducing the potential for either CF initiation or spread will decrease the likelihood of active CF. In very dense stands, thinning to reduce CBD will likely be necessary to lower active CF potential. Our results indicate that reducing surface fuel loading decreases the risk of CF even at low fuel moistures. Any method of surface fuel load reduction would decrease the likelihood of CF initiation. However, repeated use of prescribed fire not only reduces surface fuel loading, but also reduces ground fuel loading and increases the FSG by lowering surface fuel height and increasing CBH throughout stand development. Mitchell *et al*. 2014 point out that climate change may limit prescribed burning in the future by reducing the number of days that are within prescription, so a mixture of fuel treatments will likely be required to effectively manage surface and canopy fuels to reduce CF potential in the future.

Conflicts of interest

The authors declare no conflicts of interest.

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