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Effects of overstory composition and prescribed fire on fuel loading across a heterogeneous managed landscape in the southeastern USA

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ABSTRACT

In the southeastern USA, land use history, forest management and natural geomorphic features have created heterogeneous fuel loads. This apparent temporal and spatial variation in fuel loads make it difficult to reliably assess potential fire behavior from remotely sensed canopy variables to determine risk and to prescribe treatments. We examined this variation by exploring the relationships between overstory forest vegetation attributes, recent fire history, and selected surface fuel components across an 80,000 ha contiguous landscape. Measurements of dead and live vegetation components of surface fuels were obtained from 624 permanent plots, or about 1 plot per 100 ha of forest cover. Within forest vegetation groups, we modeled the relationship between individual surface fuel components and overstory stand age, basal area, site quality and recent fire history, then stochastically predicted fuel loads across the landscape using the same linkage variables. The fraction of the plot variation, i.e., R^2, explained by predictive models for individual fuel components ranged from 0.05 to 0.66 for dead fuels and 0.03 to 0.97 for live fuels in pine dominated vegetation groups. Stand age and basal area were generally more important than recent fire history for predicting fuel loads. Mapped fuel loads using these regressor variables showed a very heterogeneous landscape even at the scale of a few square kilometers. The mapped patterns corresponded to stand based forest management disturbances that are reflected in age, basal area, and fire history. Recent fire history was significant in explaining variation in litter and duff biomass. Stand basal area was positively and consistently related to dead fuel biomass in most groups and was present in many predictive equations. Patterns in live fuel biomass were related to recent fire history, but the patterns were not consistent among forest vegetation groups. Age and basal area were related to live fuels in a complex manner that is likely confounded with periodic disturbances that disrupt stand dynamics. This study complements earlier hazardous fuels research in the southeastern USA, and indicates that succession, disturbance, site quality and decomposition interact with forest management practices to create variable spatial and temporal conditions. The inclusion of additional land use, disturbance history, and soil-topographic variables coupled to improved sampling methods may increase precision and subsequent fuel mapping.

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1. Introduction

In addition to weather, topography and wildfire suppression strategies, fuel load (FL) is a critical component affecting the extent of fires that exceed control by initial attack resources. In the southeastern USA the importance of FL accumulation on wildfires is long known from empirical observations (Davis and Cooper, 1963). In addition, fire emissions are becoming a critical component in attaining air pollution standards and the quantity of emissions is directly tied to FL (Goodrick et al., 2010). The reduction in FL by frequent prescribed fire is well established from both experimental and modeling studies (Brose and Wade, 2002; Glitzenstein et al., 2006; Hanula and Wade, 2003; Hough, 1978; Waldrop et al., 2009). Yet, increases in FL could be partially responsible for the rise in large fire size occurrences since the 1970s (Scott, 2006; Malamud et al., 2005). The area treated by prescribed fire annually remains relatively static in the southeastern USA. It is typically a small fraction (<10%) of the total pine forest area (Andreu and Hermansen-Baez, 2008; Haines et al., 2001). There are concerns that the latest United States Environmental Protection Agency (2011) "National Ambient Air Quality Standards", requiring reductions in particulate matter and ozone in the USA, may curtail prescribed fire in the future. Therefore, understanding the ecological and management processes that control the temporal and spatial variation in FL is important to reliably determine risk and to pre-

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scribe treatments (Keane et al., 2001; Hiers et al., 2003; Finney et al., 2007).

1.1. Previous studies

In the southeastern USA crown fires are relatively uncommon except where pine needle drape on shrubs creates a continuous fuel ladder to the canopy (Sackett, 1975). Fire behavior is generally dominated by FL associated with litter and available fine fuels in grass and shrub components (Andreu and Hermansen-Baez, 2008; Andreu et al., 2012). These live fuels are also the largest contributors to consumption following prescribed fires (Hough, 1978; Goodrick et al., 2010). Experiments on factors influencing FL within forest stands in the southeastern USA have demonstrated the influence of recent fire history, and to a lesser degree the influences of overstory density, disturbance, vegetation type, and succession. Several studies have shown that the prescribed fire return interval is critical in reducing available FL in southern Georgia and northern Florida in pine–gallberry–palmetto (*Pinus* spp.-*Ilex glabra* (L.) A. Gray-*Serenoa repens* (Bartram) Small) vegetation (Sackett, 1975; Hough, 1978, 1982; McNab et al., 1978; Hanula and Wade, 2003). Fire frequency intervals of 2–3 years are essential to maintain low levels of both live and dead fuels (Sackett, 1975; Glitzenstein et al., 2003). Annual and biennial cycles of growing season fire eliminate the accumulations of litter and shifted the live fuel composition from woody plants to one dominated by grasses and forbs (Waldrop et al., 1987). In contrast, limited effect on woody plant cover or biomass is observed from dormant season fires (Glitzenstein et al., 1995; Brockway and Lewis, 1997; Kush et al., 1999).

Ecological studies in frequently burned areas have revealed that understory biomass of the grass-forb community decreases dramatically as pine stocking increases (Carter and Hughes, 1974; McNab et al., 1978; Harrington, 2006). In contrast, as pine density decreases, litter biomass decreases due to lower crown biomass per unit area (Boyer and Fahnestock, 1966). Studies of biomass accretion as a function of succession have shown that the forest floor litter and humus layers increase annually, and can reach equilibrium in less than a decade (Brender et al., 1976; Switzer et al., 1979). For live FL the patterns are more complex (Cain and Shelton, 2001). Shrub biomass may increase, followed by a shift to more shade tolerant shrubs, then decrease. Grasses and forbs generally decline in the early stages of succession from canopy closure and root competition (Harrington, 2006). Small trees between 2 and 12 cm diameter breast height (DBH) can shift into larger DBH classes over several decades, but natural mortality appears the dominant process influencing stem density (Peet and Christensen, 1980). The consequence of catastrophic wind disturbances, thinning and understory mastication of woody trees and shrubs has been quantified in several studies (Wade et al., 1993; Kush et al., 1999; Provencher et al., 2001; Brose and Wade, 2002; Glitzenstein et al., 2006; Ottmar et al., 2007; Waldrop et al., 2009). Finally, the influence of vegetation type (i.e., species groupings) on FL in the southeastern USA is the basis for the standard fire behavior fuel model system (Scott and Burgan, 2005) and photo series (Ottmar and Vihnanek, 2000; Ottmar et al., 2003). These model systems provide coarse scale estimates of FL. More recently, FL data have been expanded in the southeastern USA by the Fuel Characteristic Classification System (FCCS) (Ottmar et al., 2007). However, these model systems offer no basis for predicting or mapping the local distribution of fuels, and understanding processes responsible for the patterns.

1.2. Objectives

Intensive and systematic field mapping of fuel loads is rare at scales of thousands of hectares (ha) (Fernandes et al., 2006). For economic reasons, most efforts to map surface fuels are based on remote sensing approaches with corresponding low density field measurements or simple categorical assignments of standard fuel models (Keane et al., 2001; Reich et al., 2004; Rollins et al., 2004; Buckley et al., 2006; Arroyo et al., 2008). In dynamic managed ecosystems, the reliability of these data and the implied assumptions provide limited utility for guiding fire management. The objectives of our research are: (1) to quantify the forest stand relationships that structure FL, (2) to gain insight into the dominant processes controlling fuel load levels, (3) to validate ecological and management factors predicted to influence FL, particularly recent fire, and (4) to produce spatial maps of FL by linking predictive equations to mapped polygons of forest vegetation group, site quality, forest

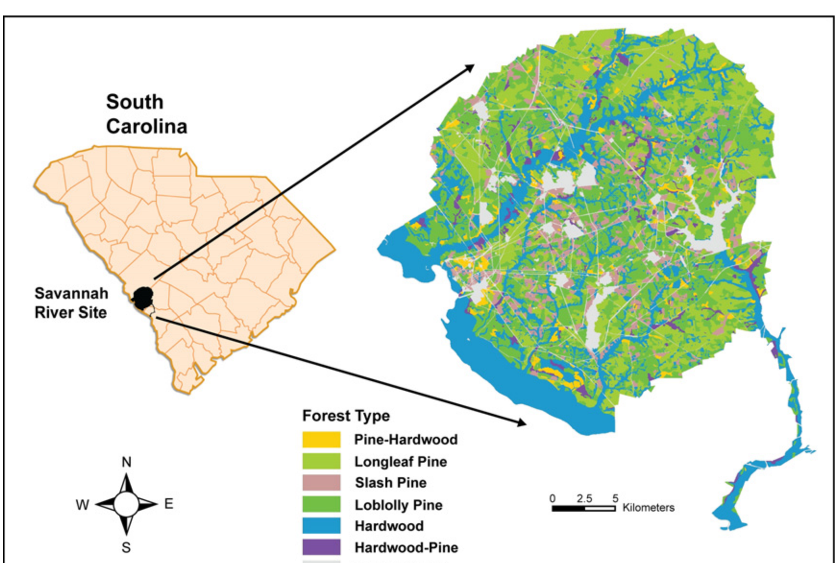

Fig. 1. The Savannah River Site in South Carolina, southeastern USA. Major forest vegetation groups are shown.

age, basal area and recent fire history. Our study evaluated FL components within the FCCS fire modeling framework (Ottmar et al., 2007). The relationship between FL, fire behavior and fire potential are described in companion papers (Andreu et al., 2012; Hollingsworth et al., 2012).

2. Study area

The United States Department of Energy Savannah River Site (SRS) is an 80,000 hectare (ha) National Environmental Research Park, near Aiken, South Carolina (Kilgo and Blake, 2005). It is located on the Upper Coastal Plain and Sandhills physiographic provinces in South Carolina, USA (Fig. 1). The site was established in 1951 on predominately agricultural farms and cutover forest lands that were subsequently reforested and managed for various natural resources compatible with the industrial missions (United States Department of Energy, 2005). Agrarian practices impacted over 70% of the landscape since European settlement in the late eighteenth century (White, 2005). When the SRS was established, approximately 33,000 ha were in old-fields and the balance consisted of cutover forest land with low stocking (Kilgo and Blake, 2005). The planting of the old fields and cutover forests with loblolly pine (*P. taeda* L.), longleaf pine (*P. palustris* Mill.) and slash pine (*P. elliottii* Engelm. var. *elliottii*; planted outside of its natural range) created a large block in a narrow age class and a potential FL problem. The hardwood dominated groups are predominately on mesic soils and poorly drained bottomlands or wetlands, with stand ages typically between 20 and 90 years (Parresol, 2004).

Today, the SRS contains approximately 74,000 ha of forested landscape divided into about 6000 stands. Prescribed fire is applied on 10,000 ha annually to restore pine savanna habitat and reduce FL. Limited areas are treated with herbicides and mechanical shredding to reduce mid-story vegetation for the endangered red-cockaded woodpecker (*Picoides borealis* Vieillot). Annually, intermediate thinning occurs on about 2000 ha and clear felling on about 300 ha (Kilgo and Blake, 2005). Wildfire frequency at SRS is relatively low compared to other Federal lands in the southeastern USA (14 vs. 78 wildfires per 100,000 ha). The regional mean occurrences of moderate (>123 ha, 0.23%) or large wildfires (>1000 ha, 0.04%) are far higher than the observed at SRS (0.003% >123 ha and none >1000 ha) (Malamud et al., 2005; Shea and Bayle, 2005). The lower incidence of large wildfires at SRS is attributed to an effective suppression program, limited public access, periodic harvests and application of prescribed fire to 10,000 ha annually. However, proposed reductions for particulate matter and ozone (United States Environmental Protection Agency, 2011) may curtail the application of prescribed fire to less than half of the SRS and lead to increases in FL.

3. Methods

3.1. Inventory design and fuels sampling

The inventory of FL was designed to provide information for multi-resource management planning. The data collected were comprised of: (1) individual tree diameters (DBH) and heights identified by species and weighted by unit-area frequencies, (2) estimates of surface FL, and (3) vertically distributed live vegetation crown volume estimates and cover by species. The original layout of sample points was installed in 1989 to establish a continuous forest inventory. The plots were established on a 1000 by 1000 m grid over the entire land base. This grid resulted in approximately 1 sample plot per every 100 ha of forest. The surface FL and live vegetation measurements were incorporated into the 1999 inventory. A total of 624 plots were sampled in the forest areas excluding the Savannah River swamp and delta forest. The plot design was a standard design commonly used in the southeastern USA (United States Forest Service, 1985). It consisted of a cluster of five subplots spaced 21.34 m apart. Two nested plots were established within each of these five subplot center points. One of the nested plots was a variable-radius plot in which an 8.61 basal area factor ($m^2\ ha^{-1}$) prism was used for sampling overstory trees 12.7 cm or larger in DBH. The second nested plot was a circular fixed-radius 13.5 m^2 plot for sampling small trees from 2.5 to 12.7 cm in DBH. For trees on both plots, DBH, species, crown base height, and total tree height were measured. All prism sampled trees from the five subplots were combined, and therefore the operative prism factor for the sample location was 1.72, and the cumulative area of the fixed-radius plots is 67.5 m^2. The plot angle was rotated (ca. 1/3 of the plots) to insure that all subplots fell within the same forest condition found at subplot 1. Subplot 1 was never moved from the initially selected point location. Ages of selected dominant or co-dominant trees on subplot 1 were obtained from cores and site quality was determined by using site index tables for southern species at base age 50 years (United States Forest Service, 1985).

3.2. Downed woody material, litter, and duff sampling

Four planar transects were used between the five subplots for measuring forest floor litter[1] depth, duff[2] depth, and downed woody material (DWM) according to standard size classes representing moisture time lags (Van Wagner, 1968; Brown, 1974). To measure DWM, counts along a vertical-plane-intersect plot were made. A 3.05 m section of the transect line was used for pieces with diameters of $\leqslant$0.63 cm (1-h (hr)) and diameters of 0.64–2.54 cm (10-h). Counts were made of pieces with diameters of 2.55–7.62 cm (100-h) along a 6.1 m transect. DWM larger than 7.62 cm diameter encountered along the full 21.34 m transect had their individual diameters at the point of intersection measured to the nearest 0.25 cm. Their condition was classed as either sound wood (1000-h sound) or rotten wood (1000-h rotten). Eight measurements of litter and duff depth to the nearest 0.25 cm were taken at 3.05 m intervals along each of the 21.34 m transect lines.

3.3. Live fuel sampling

Live FL components were determined using vegetation profile data based on Forest Inventory and Analysis procedures (United States Forest Service, 1985). The species were grouped into various life forms. The vegetation life forms are identified by 8 broad species classes: yellow pines, other softwoods, hardwoods, tropicals, shrubs, vines, grasses and grass like (graminoids), and forbs and others[3]. A circular plot with a 10.67 m radius was established around each subplot 1. Height zones appropriate to the vegetation forms were measured to the nearest 3 cm. Each zone was assigned a percent volume occupied to the nearest percent and each layer within a zone was assigned a relative coverage by vegetation form such that they add up to 100%. Live vegetation cover estimates were made during the growing season. Small trees taller than 1.4 m were removed from the vegetation profile data and placed in the understory tree layer to match FCCS protocol for fire potential

[1] Litter is the loose layer made up of twigs, dead grasses, recently fallen leaves, needles and so forth where the individual pieces are still identifiable and little altered by decomposition.

[2] The duff layer lies below the litter layer and above the mineral soil. It is made up of litter material that has decomposed to the point that the individual pieces are no longer identifiable. The duff layer is generally darker than the litter layer and is more aggregated because of the fine plant roots growing in the duff material.

[3] Forbs are herbaceous flowering plants that are not graminoids (grasses, sedges and rushes). Other plants in the broad species group 8 include ferns and mosses.

computations. Because nearly all shrubs beneath a pine overstory contain needle drape during the dominant wildfire and prescribed fire months (December through April) unless they were just burned, we did not quantify this variable. The FCCS model treats needle drape as a presence or absence variable to make fire potential calculations.

3.4. Fuel load computation

3.4.1. Small trees

For small trees in the understory and mid-story layers above shrubs (i.e., non-merchantable arborescents of *Pinus*, *Juniperus*, *Taxodium* <12.7 cm DBH and hardwoods <15.24 cm DBH) the eastern USA biomass equations of Brown et al. (1997) were utilized. His equations pooled all hardwood species into one data set and all of the conifer species into a second data set, which were fit to the following nonlinear functions:

$$\text{Hardwoods}: W = \frac{0.5+25{,}000D^{2.5}}{D^{2.5}+246{,}872}$$

$$\text{Conifers}: W = \frac{0.5+15{,}000D^{2.7}}{D^{2.7}+364{,}946}$$

where W is aboveground dry biomass in kg per tree and D is tree diameter.

3.4.2. Downed woody material, litter, and duff

The DWM subcomponents were converted to biomass using formulas from Brown (1974). These formulas to compute Mg ha^{-1} are:

$$0-\text{to }7.62\text{-cm material} := \frac{552.31\times n\times d^2\times s\times a\times c}{L}$$

$$>7.62\text{-cm material} := \frac{552.31\times \Sigma d^2\times s\times a\times c}{L}$$

where n is number of particles counted in each size class along a line transect, d is average particle diameter for the 0- to 7.62-cm size classes or d is measured diameter for pieces >7.62 cm, s is wood specific gravity, a is the non-horizontal angle correction factor that weights estimates because all particles do not lie horizontally, c is the slope correction factor for converting Mg ha^{-1} on a slope basis to a horizontal basis, and L is the transect length in meters. The percent slope was measured at each inventory plot and the slope correction factor was calculated as $c=\sqrt{1+(\text{percent slope}/100)^2}$. The values for average d^2, s, a, and L are parameters derived from a previous SRS study by Scholl (1996) and are listed in Table 1.

The litter and duff depth measurements taken along transects were averaged for each inventory plot. Bulk density conversion factors were determined from a companion bulk density study of a stratified random sample of 97 of the 624 plots from a matrix of forest age classes, forest vegetation group, and recent fire history (Maier et al., 2004; Parresol, 2005). These bulk density values were applied to the averaged depth value for each plot to compute litter and duff loadings in Mg ha^{-1}.

Table 1
Values for average d^2 (particle diameter), s (green specific gravity), a (non-horizontal angle correction factor), and L (transect length) used in downed woody material fuel calculations at the Savannah River Site. Parameter values are from Scholl (1996).

Size class	d^2 (cm^2)	s	a	L (m)
0–0.63 cm	0.0974	0.7	1.13	12.19
0.64–2.54 cm	1.8645	0.7	1.13	12.19
2.55–7.62 cm	17.8064	0.58	1	24.38
>7.62 cm sound	–	0.58	1	85.34
>7.62 cm rotten	–	0.3	1	85.34

3.4.3. Live fuels

We computed vegetation biomass with allometric equations based on percent cover. From the vegetation profile data the percent coverage (X) of each broad species class was calculated as the product of the zone percent (Z) and the layer percent (L), i.e., $X=Z\times L/100$. The general allometric relation is

$$Y=aX^b,$$

where Y is plant biomass (Mg ha^{-1}), and a and b are coefficients specific to a broad species class or group of classes. The coefficients are from the following sources: for graminoids, Ohmann et al. (1981); for forbs and others, Siccama et al. (1970) and Whittaker (1966); and for seedling trees, shrubs and vines, Ohmann et al. (1981). These allometric equations produced average values in close agreement with total live woody and non-woody fuel biomass measured by direct harvest and weighing from three previous independent FL studies conducted on the SRS at similar plot scales (Goodrick et al., 2010).

3.5. Forest vegetation groups

For analysis purposes we grouped the plots into six forest vegetation groups (Table 2, Fig. 1) as these groups reflect land use and geomorphic conditions. For each of the inventory plots a forest vegetation group was assigned based on each individual plot species make-up, by applying the following definitions. To be assigned to one of the three pine groups, 70% or more of the total basal area of the stand must be in pine, and then it is assigned to a particular pine species based on the actual species (loblolly, longleaf, or slash pine) with the largest basal area component. To be assigned to the pine-hardwood group the plot must have ⩾50% but <70% of the total basal area in pines species. To be assigned to the hardwood-pine group the plot must have >30% but <50% of the total basal area in pine species, and to be assigned to the hardwood group, <30% of the total stand basal area must be in pine species.

3.6. Analyses of fuel relationships

3.6.1. Linkage variables to stand conditions

We followed the approach of Moeur and Stage (1995) and used canonical correlation theory on a set of variables common to both the FL inventory and the existing stand database variables. We assigned intact, unmodified plot-level data from the FL inventory database to the stands database that is linked to a stands spatial polygon layer. We focused on using the stands linkage variables and the FL inventory database to parameterize linear and nonlinear stochastic predictor regressions that mimic within-polygon variation. All analyses were stratified by forest vegetation group (Table 2) as preliminary analyses showed significant differences among the six forest vegetation groups (Parresol, 2004; Parresol et al., 2006). A limited number of stand linkage variables were available: (1) stand age in years (A); (2) stand basal area in m^2 ha^{-1} (B); (3) site index in meters, base age 50 years (S); (4)

Table 2
Six forest vegetation groups, excluding the swamp and delta forests, at the Savannah River Site.

Vegetation group	Number of stands	Area (hectares)	Area (%)	Number of plots
Loblolly pine	1986	25,042	35.54	278
Longleaf pine	1263	17,906	25.41	133
Slash pine	630	6259	8.88	58
Pine-hardwood	293	2250	3.38	23
Hardwood-pine	225	2201	3.30	27
Hardwood	1787	16,803	23.85	105
Total	6184	70,461	100.00	624

years since last prescribed fire (Y); and (5) number of times burned since 1971 or since stand establishment (N). If number of burns was 0 in the dataset then years since last burn was assigned the value 33. Stand specific records were maintained beginning in 1971. Prior to that year, the area treated annually averaged less than 1000 ha.

We did not fully explore interaction of independent stands linkage variables, because in many cases there were no logical bases for constructing them. There is the potential for multicollinearity in the regression equations. While this does not affect prediction, it can affect interpretation of the models. A common approach to detect collinearity in the p explanatory variables is to examine the correlation matrix **R**. However, it has been pointed out by many statisticians (e.g., Belsley et al., 1991; Freund and Wilson, 1998; Kleinbaum et al., 2008) that the use of **R** has many shortcomings as a diagnostic measure for multicollinearity. These authors recommend constructing a collinearity diagnostic for the data matrix **X** called the condition number (CN) (for details see Belsley et al., 1991). If CN <30 this indicates week dependencies in **X**, $30 \leqslant \text{CN} \leqslant 100$ indicates moderate dependencies and CN > 100 indicates strong dependencies. We followed the later approach and determined CN for each equation.

3.6.2. Regression, variance components and stochastic prediction

We used the following generalized procedure for regression analysis to establish the variance components and make stochastic predictions for each stand polygon. Let W_{ij} be dry-weight mass (Mg ha^{-1}) for the ith forest vegetation group ($i = 1, \ldots, 6$) (see Table 2) and the jth FL component ($j = 1, \ldots, 13$) (see Table 3). A general expression for our FL component regression models (linear or nonlinear) is

$$W_{ij,t} = f(\boldsymbol{\lambda}_{ij,t}, \boldsymbol{\beta}_{ij}) + \varepsilon_{ij,t} \tag{1}$$

where $\boldsymbol{\lambda}_t$ is a $(K \times 1)$ vector of linkage variables, $\boldsymbol{\beta}$ is a vector of parameters, ε_t is a random error, and t represents the tth observation $(t = 1, 2, \ldots, T)$. Now $\varepsilon_{ij,t}$ has properties $E[\varepsilon_{ij,t}] = 0$ and $\text{var}[\varepsilon_{ij,t}] = \sigma^2_{ij}$. Regression models, in general, have two quantifiable sources of error: (1) variance of the mean, which changes with distance from centroid of regressor variables; and (2) population variance (i.e., σ^2). These variance components were used to construct stochastic predictors for imputing values on the landscape such that natural ecosystem variability was mimicked at the landscape scale. The general form of the stochastic predictors is

$$\hat{W}_{ij} = f(\boldsymbol{\lambda}_{ij,0}, \hat{\boldsymbol{\beta}}_{ij}) + \{F^{-1}_{U_1}[\boldsymbol{\lambda}'_{ij,0}(\boldsymbol{\Lambda}'_{ij}\boldsymbol{\Lambda}_{ij})^{-1}\boldsymbol{\lambda}_{ij,0}]^{1/2} + F^{-1}_{U_2}\}\hat{\sigma}_{ij} \tag{2}$$

where $\boldsymbol{\Lambda}_{ij}$ is the T by K matrix of linkage variables from the ijth subset, $\boldsymbol{\lambda}_0$ is the value of the linkage variables for which stochastic predictions are being made, F^{-1}_U is the inverse of the standard normal distribution function, the U_r's are independent uniform random variates on the interval [0,1], and the $\hat{\sigma}_{ij}$'s are the root mean square errors from the fits of Eq. (1).

3.6.3. Logistic function for presence/absence of 1000-h fuel

Many stands had no 1000-h fuels (a large proportion of zeros) so it was necessary first to predict presence/absence using the logistic function (Appendix B) before assigning a value to the stands based upon forest composition, age and basal area. Unless catastrophic wind or ice storms occur, the quantity of this size class of material is generally very low in managed stands (McMinn and Hardt, 1996). To handle this situation, a series of logistic models were fitted by maximum likelihood:

$$\text{logit}(p_{il}) = \boldsymbol{\lambda}'_{il}\boldsymbol{\beta}_{il} + \varepsilon_{il} \tag{3}$$

where logit(p) is the odds ratio that an event will occur, p indicates the probability of occurrence of 1000-h fuel, ε is a binomially distributed random variable, and the ilth subset represents the ith forest vegetation group and the lth 1000-h fuel component ($l = 1$ for sound fuel and $l = 2$ for rotten fuel). After being fitted, Eq. (3) expressed in terms of probability becomes:

$$\hat{p}_{il} = [1 + \exp(-\boldsymbol{\lambda}'_{il}\hat{\boldsymbol{\beta}}_{il})]^{-1} \tag{4}$$

In applying Eq. (4), cut-off probabilities were chosen that maximized the classification accuracy of the ilth subset. If Eq. (4) indicated presence of 1000-h fuel, then Eq. (2) was employed to compute values.

Table 3
Average ± standard deviation (minimum/maximum) values in Mg ha^{-1} for wildland fuel component biomass.

Fuel component	Forest vegetation group						
	Loblolly pine	Longleaf pine	Slash pine	Pine-hardwood	Hardwood-pine	Hardwood	Overall average
Litter	5.81 ± 2.33 (0.65/12.75)	6.50 ± 3.94 (0.00/18.77)	6.94 ± 2.57 (1.57/12.69)	5.68 ± 2.42 (1.18/11.98)	5.57 ± 2.10 (1.45/10.64)	5.74 ± 2.73 (0.00/11.30)	6.04 ± 2.85 (0.00/18.77)
Duff	8.84 ± 6.23 (0.00/32.92)	8.04 ± 6.86 (0.00/31.02)	12.54 ± 7.52 (0.00/41.56)	6.69 ± 3.51 (0.00/12.56)	8.60 ± 3.74 (1.32/18.31)	6.62 ± 4.13 (0.00/21.44)	8.52 ± 6.21 (0.00/41.56)
1-h	0.18 ± 0.13 (0.00/1.01)	0.07 ± 0.09 (0.00/0.76)	0.15 ± 0.18 (0.00/0.92)	0.21 ± 0.17 (0.02/0.73)	0.28 ± 0.21 (0.06/0.95)	0.23 ± 0.17 (0.00/1.18)	0.17 ± 0.15 (0.00/1.18)
10-h	2.44 ± 1.66 (0.15/12.68)	1.48 ± 1.14 (0.00/6.12)	2.36 ± 1.50 (0.45/6.57)	1.94 ± 1.04 (0.30/4.03)	2.05 ± 0.79 (0.60/4.05)	2.08 ± 1.41 (0.00/8.20)	2.13 ± 1.50 (0.00/12.68)
100-h	2.31 ± 2.29 (0.00/15.68)	2.37 ± 2.64 (0.00/16.71)	2.39 ± 2.01 (0.00/12.53)	2.12 ± 2.15 (0.00/8.88)	2.76 ± 1.74 (0.00/7.87)	2.31 ± 2.54 (0.00/15.66)	2.36 ± 2.37 (0.00/16.71)
1000-h sound	1.11 ± 2.68 (0.00/20.13)	1.82 ± 4.07 (0.00/22.09)	2.20 ± 3.66 (0.00/16.16)	3.27 ± 6.96 (0.00/27.03)	1.82 ± 2.61 (0.00/7.90)	1.85 ± 4.00 (0.00/27.15)	1.66 ± 3.74 (0.00/28.00)
1000-h rotten	2.29 ± 7.21 (0.00/98.09)	2.18 ± 4.28 (0.00/29.63)	2.90 ± 2.61 (0.00/10.13)	1.79 ± 2.93 (0.00/13.52)	3.06 ± 4.22 (0.00/16.16)	2.35 ± 4.26 (0.00/26.61)	2.36 ± 5.62 (0.00/98.09)
Small trees	14.11 ± 10.84 (0.00/65.76)	8.10 ± 11.00 (0.00/59.32)	10.92 ± 9.90 (0.00/45.00)	16.10 ± 16.16 (0.00/72.90)	19.25 ± 18.07 (0.00/71.31)	19.75 ± 13.66 (0.00/61.48)	13.79 ± 12.48 (0.00/72.90)
Seedlings	0.22 ± 0.13 (0.00/0.67)	0.22 ± 0.14 (0.01/0.77)	0.22 ± 0.14 (0.04/0.77)	0.19 ± 0.11 (0.04/0.47)	0.22 ± 0.11 (0.08/0.45)	0.21 ± 0.13 (0.00/0.56)	0.22 ± 0.13 (0.00/0.77)
Shrubs	0.20 ± 0.15 (0.00/0.74)	0.19 ± 0.14 (0.00/0.59)	0.13 ± 0.12 (0.00/0.46)	0.18 ± 0.11 (0.00/0.38)	0.21 ± 0.18 (0.00/0.68)	0.20 ± 0.15 (0.00/0.71)	0.19 ± 0.15 (0.00/0.74)
Vines	0.22 ± 0.14 (0.00/0.68)	0.15 ± 0.13 (0.00/0.60)	0.20 ± 0.14 (0.00/0.59)	0.17 ± 0.12 (0.02/0.39)	0.17 ± 0.12 (0.04/0.42)	0.18 ± 0.13 (0.00/0.52)	0.19 ± 0.14 (0.00/0.68)
Grasses	0.13 ± 0.18 (0.00/1.52)	0.19 ± 0.21 (0.00/1.02)	0.08 ± 0.09 (0.00/0.54)	0.14 ± 0.16 (0.00/0.50)	0.19 ± 0.25 (0.00/0.78)	0.28 ± 0.33 (0.00/1.55)	0.16 ± 0.22 (0.00/1.55)
Forbs	0.02 ± 0.03 (0.00/0.30)	0.02 ± 0.04 (0.00/0.29)	0.01 ± 0.02 (0.00/0.15)	0.02 ± 0.02 (0.00/0.11)	0.02 ± 0.05 (0.00/0.27)	0.02 ± 0.03 (0.00/0.17)	0.02 ± 0.03 (0.00/0.30)

4. Results

4.1. Fuel loadings

The means, standard deviations and ranges of biomass values for the 13 FL components are contained in Table 3. The litter and duff components average 6.0 and 8.5 Mg ha^{-1}, respectively. The maximum value for litter is 18.8 Mg ha^{-1}, and the maximum duff value is 41.6 Mg ha^{-1}. The other higher duff loading plots are generally 20–30 Mg ha^{-1} and are plots located in unburned pine stands. The slash pine vegetation group stands out with the highest duff average of 12.5 Mg ha^{-1}. The 1-, 10-, 100-, 1000-h sound and 1000-h rotten FL averages (maximums) are 0.17 (1.2), 2.13 (12.7), 2.36 (16.7), 1.66 (28.0) and 2.36 (98.1) Mg ha^{-1}, respectively. The longleaf pine group has much lower amounts of 1- and 10-h fuels compared to the other forest vegetation groups.

Woody biomass ranges from 0 to 0.77 Mg ha^{-1} for seedlings with a mean of 0.22 Mg ha^{-1}, 0 to 0.74 Mg ha^{-1} for shrubs with a mean of 0.19 Mg ha^{-1}, and 0 to 0.68 Mg ha^{-1} for vines with a mean of 0.19 Mg ha^{-1}. Non-woody biomass ranges from 0 to 1.55 Mg ha^{-1} for grasses with a mean of 0.16 Mg ha^{-1}, and from 0 to 0.3 Mg ha^{-1} for forbs with a mean of 0.017 Mg ha^{-1}. The grand mean of all live fuels, exclusive of small trees, is only 0.16 Mg ha^{-1}. The average biomass of 13.8 Mg ha^{-1} for small trees is much larger than all other FL components with the longleaf group having a much lower amount of small tree biomass (8.1 Mg ha^{-1}).

4.2. Equations, coefficients of determination and critical linkage variables

The majority of the modeled equations are log-linear functions followed by exponential functions (Appendix A). All equations are nonlinear in their response. Most equations have highly significant *P*-values, even if the coefficient of determination (R^2) value is low. The R^2 for the predictive models range from 0.05 to 0.66 for dead fuels and 0.03 to 0.97 for live fuels in pine dominated vegetation groups. Collinearity was not an issue in the majority of the equations (Table 4). Only 7 equations (9%) have moderate to strong multicollinearity (CN > 30) and only one of those has CN > 100. Live fuels tend to have larger CN values. Based upon the frequency at which the variables occurred in the FL predictive equations, the relative importance of the independent variables rank basal area (31) > age (22) > site index (21) > years since last burn (14) = number of burns (14) for dead fuels, and basal area (26) > site index (24) > age (20) > number of burns (16) > year since last burn (13) for live fuels. Both stand basal area and age tend to dominate the predictive equations, often in conjunction with site index.

The R^2 values among dead fuels are generally highest for litter and duff. In pine and pine-hardwood groups the litter R^2 range from 0.42 to 0.66 and for duff the values range from 0.45 to 0.64. The comparable R^2 values are generally lowest for the 1000-h components and in some cases the *P*-values are non-significant. The R^2 values range from 0.04 to 0.33 for the 1000-h sound material. In contrast, the R^2 for the 1000-h fuel in the hardwood-pine group is 0.79 for sound material and 0.55 for rotten material. The hardwood group has low R^2 values for all dead FL components. For example the hardwood group litter and duff R^2 values are only 0.08 and 0.23, respectively. These hardwood values compare with the litter and duff R^2 values in the longleaf group of 0.66 and 0.58, respectively, and in the pine-hardwood group of 0.66 and 0.50, respectively.

Among the live FL components, there are few consistent patterns among vegetation groups and FL components. The R^2 values are consistently highest (0.54–0.97) in the pine-hardwood group and consistently low in the loblolly group (0.03–0.33). The highest R^2 values occur with the pine-hardwood group for grasses and forbs (R^2 values >0.9) with strong collinearity among regressor variables, especially in the forbs equation. Under loblolly, the grasses have the highest R^2 (0.33) followed by the forbs (0.14). Under longleaf, small trees (0.51) and grasses (0.49) have the highest values. With slash pine the shrubs (0.56) and the forbs (0.93) have the highest R^2 values, and three equations (small trees, shrubs, grasses) possess collinearity. In the hardwood-pine group the highest R^2 is for grasses (0.41) and in the hardwood group for forbs (0.48).

4.3. Coefficient signs

With respect to the coefficients of the regression equations, results for dead fuels are reported separately from live fuels. For the dead fuels in the pine dominated groups the age coefficients, when significant, are on the whole mixed. Age is positive for the loblolly and longleaf pine FL components except the 1-h fuel and the sign is negative for litter and 100-h slash pine fuels (Table 4). For hardwood groups, the age sign is more complex and reveals no obvious pattern. The basal area variable appears consistently in predictions of dead FL in the various groups. Both litter and duff are positively related to basal area across all groups. For other dead FL components the basal area signs vary. When the variable "years since last burn" is significant, it is positively correlated with litter.

For the live fuel components, the relationships to the stand variables appear more complex (Table 4). Age frequently shows a negative relationship to live FL biomass across both pine and hardwood groups except for vines which consist primarily of *Smilax* spp., *Toxicodendron radicans* (L) Kuntze ssp. *radicans* and *Bignonia capreolata* L. Where a significant basal area relationship exists as a predictor of small trees, the coefficients are consistently positive for all groups, including hardwoods. Generally positive basal area coefficients for the other live fuel components are also observed in the hardwood, hardwood-pine, and slash pine groups. For small trees there is largely no effect of years since last burn or number of burns, except the negative coefficient observed in the loblolly group. In the case of forbs, biomass increases with number of burns in the hardwood groups. Contrasting or conflicting patterns in the coefficients exists among vegetation groups. Live FL coefficients for years since last burn and number of burns in the slash pine are negative and in the pine-hardwood group are positive. A similar contrasting sign pattern in live FL is also evident in the hardwood group (largely negative) and hardwood-pine group (largely positive).

4.4. Response surfaces and fuel map patterns

Response surfaces provide insights into the interplay between the variables. Graphs for each forest vegetation group for representative FL components are presented in Fig. 2. For the loblolly pine group, Fig. 2a illustrates the trend for duff to increase with age and also rapidly increase with years since last burn. The 1-h fuel increases with years since last burn, but decreases with age (Fig. 2b). For the longleaf pine group, Fig. 2c presents a pattern for litter similar to loblolly pine duff. Litter biomass increases asymptotically with years since last burn and as basal area increases. Grasses decline dramatically with stand age and basal area (Fig. 3d). In the slash pine group, litter FL increases linearly with basal area and declines with the number of burns (Fig. 2e). Shrub biomass decreases rapidly to very low levels with 3 or more burns (Fig. 2f).

Response surfaces for hardwood and mixed hardwood vegetation groups illustrate similar multidimensional relationships to the linkage variables. In the pine-hardwood group, the 100-h fuel

Table 4
Wildland fuel component regression coefficient signs, coefficient of determination (R^2) and collinearity condition number (CN) for best predictive equations in Appendix A. Regressor variables are stand age in years (A), basal area in m^2 ha^{-1} (B), site index in m base 50 years (S), and recent fire history as years since last prescribed fire (Y) or number of burns since 1971 or since stand establishment (N). The equation R^2 values with P-values > 0.05 are underlined.

Forest vegetation group		Fuel component	Coefficient signs on regressor variables A	B	S	Y	N	R^2	CN[a]
Loblolly pine	dead fuels	Litter		+		+		0.423	1.1
		Duff	+	+	+	+		0.531	1.9
		1-hour	–	+		+		0.111	1.8
		10-hour		+			+	0.050	1.0
		100-hour	+	–	+	–		0.145	1.9
		1000-hour sound	+	–				0.039	2.1
		1000-hour rotten	+					0.032	1.0
	live fuels	Small trees	–	+			–	0.190	1.8
		Seedlings		–	+			0.069	1.2
		Shrubs	–			+		0.036	1.2
		Vines			+			0.028	1.0
		Grasses		–	+			0.328	23.6
		Forbs		–				0.144	1.0
Longleaf pine	dead fuels	Litter	+	+		+		0.656	2.8
		Duff	+		+			0.578	1.2
		1-hour	–		–		–	0.109	1.3
		10-hour	+	–		–		0.084	2.8
		100-hour	+	–				0.106	2.8
		1000-hour sound	+	–				0.122	3.3
		1000-hour rotten		–	+			0.056	1.3
	live fuels	Small trees	–	+	–	+		0.513	25.2
		Seedlings		–	–	+		0.147	18.7
		Shrubs	–		–			0.176	17.0
		Vines	+		+			0.052	21.6
		Grasses	–	–	–			0.494	22.0
		Forbs	–		–			0.224	1.2
Slash pine	dead fuels	Litter	–	+			–	0.620	2.7
		Duff		+	+		–	0.645	1.3
		1-hour		+				0.119	1.0
		10-hour		+		–		0.172	1.2
		100-hour	–			–		0.142	1.0
		1000-hour sound			+			0.131	1.0
		1000-hour rotten			+			0.027	1.0
	live fuels	Small trees	–	+	–			0.261	32.8*
		Seedlings	–			–	–	0.398	9.7
		Shrubs	+		–	–	–	0.562	31.5*
		Vines		+		–	–	0.138	12.6
		Grasses	–	+	+	–	–	0.120	52.7*
		Forbs	–					0.931	1.9
Pine-Hardwood	dead fuels	Litter	+/–	+/–	+/–	–		0.658	18.8
		Duff		+			+	0.500	1.2
		1-hour	+		+			0.247	1.1
		10-hour		+				0.316	1.0
		100-hour	+	–	+			0.627	2.6
		1000-hour sound			+		–	0.334	1.3
		1000-hour rotten		–	+		–	0.219	3.0
	live fuels	Small trees		+	–		+/–	0.543	11.8
		Seedlings		–	+			0.693	23.1
		Shrubs	–		–	+		0.574	15.4
		Vines	+	–			+	0.598	10.4
		Grasses	–	–	+	+	+	0.975	83.1*
		Forbs		–	+	+	+	0.920	130.7**
Hardwood-Pine	dead fuels	Litter	+/–	+	+	+/–	+/–	0.459	19.4
		Duff	+/–			+/–	+/–	0.450	40.5*
		1-hour		–				0.116	1.0
		10-hour	–		–			0.242	1.3
		100-hour		–	–		+	0.080	1.2
		1000-hour sound		+	–		+	0.793	1.4
		1000-hour rotten	–		+	–		0.552	1.3
	live fuels	Small trees	+		+/–			0.394	4.8
		Seedlings		+			–	0.270	9.3
		Shrubs	–	–	–			0.103	1.3
		Vines		–		+	+	0.297	13.8
		Grasses		+				0.409	11.4
		Forbs		+			+	0.299	1.4

(*continued on next page*)

Table 4 (*continued*)

Forest vegetation group		Fuel component	Coefficient signs on regressor variables: A	B	S	Y	N	R^2	CN[a]
Hardwood	dead fuels	Litter		+	–	+		0.080	1.5
		Duff		+				0.233	1.0
		1-hour		+				0.253	1.0
		10-hour		+			+	0.164	1.2
		100-hour	–	+	+		+	0.116	3.1
		1000-hour sound		–	+			0.026	1.8
		1000-hour rotten	+	–		–	–	0.186	3.3
	live fuels	Small trees	–	+	+			0.193	1.9
		Seedlings		+	+	–	–	0.078	20.8
		Shrubs	–	+	–		–	0.111	3.1
		Vines		+	+			0.169	1.3
		Grasses		–	+		–	0.153	1.6
		Forbs	–	+		+	+	0.481	75.3*

[a] CN < 30 indicates weak dependencies among regressor variables, 30 ⩽ CN ⩽ 100 indicates moderate dependencies (*) and CN > 100 indicates strong dependencies (**) (Belsley et al., 1991).

increases sevenfold over the span from 10 to 80 years, but changes little with basal area (Fig. 2g). A distinct curvilinear increase in forbs is evident in response to the number of burns (Fig. 2h). However the forbs biomass is essentially zero at basal areas greater than 10 m^2 ha^{-1} regardless of the number of burns. Although the collinearity number is strong for this overall predictive equation, Pearson's correlation is not significant between number of burns and basal area (*P*-value = 0.33). Seedling biomass in the hardwood-pine group declines with the number of burns (Fig. 2i) similar to shrubs in the slash pine group. For vines in the hardwood-pine group there is very little effect of years since last burn when compared to basal area (Fig. 2j). In the hardwood group the 1000-h rotten fuel increases with age fivefold, but is reduced to very low levels as the number of burns equals or exceeds 3 (Fig. 2k). Finally small trees, which are a large fraction of the average live FL, show a very large increase with increasing basal area, but a relatively small change with age (Fig. 2l).

The spatial distributions of four key FL components, litter, duff, grasses and shrubs are illustrated in Fig. 3. These distributions are the result of linking stand polygon layers via the linkage variables using equations in Appendix A. The inclusion of stochastic prediction (Section 3.4.2) means that the statistical uncertainty in the modeling equations is represented in the assignment of values. The forest vegetation groups in Fig. 3 are predominantly upland pine and pine-hardwood. The straight lines identify original farm field boundaries dating from 1951 intermixed with forest fragments. The map area is only 25 km^2, but represents the full range of values for these FL components and the heterogeneous nature of the landscape. At the time of this inventory the dark areas that represent higher FL of litter, duff, and shrubs are generally older stands that have not been burned or harvested and include several non-managed ecological reserves. The high shrub loading in the northeastern section above the road in Fig. 3d corresponds to an ecological reserve in which no management or prescribed fire has occurred for 40–50 years. Across the mapped areas in Fig. 3, those stands with high grass FL generally have low duff and shrub FL.

5. Discussion

In agreement with Fernandes et al. (2006), the study demonstrates the potential value of performing resource inventories that incorporate FL data collection. It also supports their finding that FL is largely influenced by forest structure. The results provide fine scale spatial detail of FL for planning (e.g., Hiers et al., 2003) that is not generally available from coarse scale models of the landscape (Hollingsworth et al., 2012), but clearly highlight the challenges associated with unexplained variation. The results also give insights into the interplay between forest management and ecological processes.

5.1. Fuel loads at SRS

Comparisons indicate that indirect methods can provide reasonable biomass estimates for large surveys. The estimated average biomass of live fuel of 0.16 Mg ha^{-1} is lower than live fuel estimates in the southeastern USA (Brockway and Lewis, 1997; Carter and Hughes, 1974; Hough, 1978, 1982; McNab et al., 1978; Hanula and Wade, 2003). The low values have implications for fire behavior because live fuels required to enhance flame length and reaction intensity and carry a surface fire to tree crowns are not generally evident (Fig. 3c and d). Based on previous ecological studies of plant communities at SRS (Imm and McLeod, 2005), we interpret the low average levels of live fuel biomass (excluding small trees) as a likely result of the agricultural history of the SRS (White, 2005) and generally sandy, low organic matter and water holding capacity of the upland soils (Kolka et al., 2005), rather than the method for estimation. However, as the forest begins to age and species assemblies are restored, we anticipate that the levels of understory cover and biomass will increase.

With respect to specific components (Table 3), the maximum value for grasses is representative of high levels of biomass found in other studies on open pine savanna sites in the southeastern USA (Carter and Hughes, 1974) and on old-fields at SRS (Odum,1960). Although forb biomass is low, these lower values are characteristic of pine plantations and pine-oak forests in Alabama (Joyce and Mitchell, 1989). The mean and range for small trees is similar to reported values from surveys done in South Carolina to assess the availability of biomass for biofuels (Conner et al., 2009). The levels of dead FL are also typical for the region, which is consistent with the expectation that the dominant overstory conditions control the level of input. Litter and duff components are comparable to previous direct measures of total weight in independent studies on SRS (Maier et al., 2004; Goodrick et al., 2010) as well as other measurements in the southeastern USA (Brender et al., 1976; Switzer et al., 1979; Hough, 1978, 1982; McNab et al., 1978; Hanula and Wade, 2003). The biomass of 1- and 10-h fuels is also comparable to reported values in other southeastern USA systems (Bailey and Mickler, 2007).

5.2. Reliability of equations for interpretation and mapping

Most of the equations (>90%) are not influenced by moderate to strong collinearity, as reflected in the CN values, that could

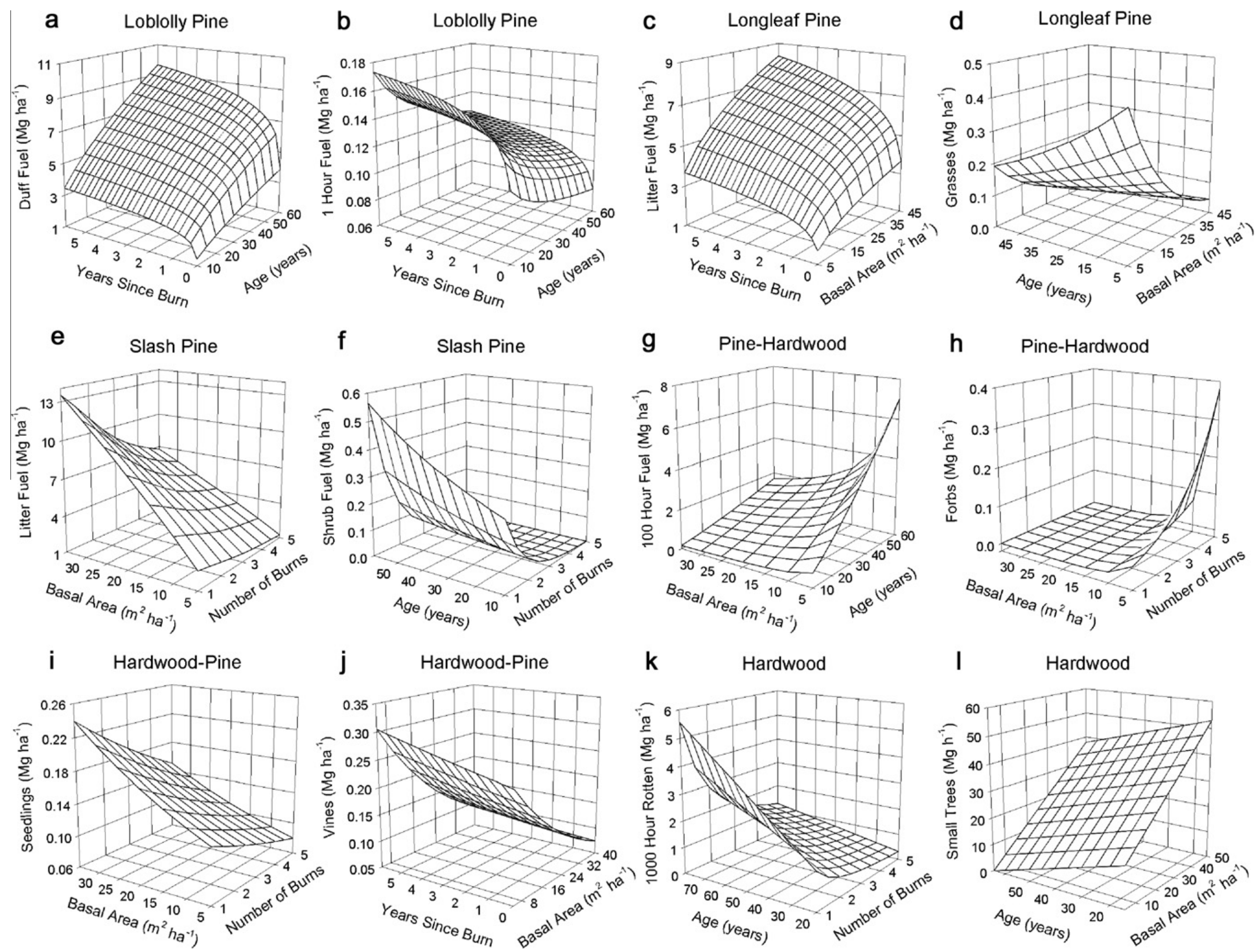

Fig. 2. Response surfaces for duff (a) and 1-h fuel (b) in loblolly pine; for litter (c) and grasses (d) in longleaf pine; for litter (e) and shrubs (f) in slash pine; for 100-h fuel (g) and forbs (h) in pine-hardwood; for seedlings (i) and vines (j) in hardwood-pine; and for 1000-h rotten (k) and small trees (l) in hardwoods as a function of stand variables and recent fire history.

compromise interpretation (Table 4). Six of the seven equations with moderate to strong collinearity are in live fuels. Many of the fuel components have fits to the linkage variables, such as the litter, duff, small trees, grasses, forbs and shrubs, within forest vegetation groups that indicate FL maps can represent actual spatial variation on the landscape. However, some components had low R^2 values, meaning much of the variation in the FL components is not captured by the linkage variables. As the estimators are unbiased, predicted values aggregated over hundreds of hectares can lead to more precise mean values, but only by compromising the small scale spatial resolution. The use of stochastic predictors to predict values for the stands ensures that the uncertainty is represented in the mapping process. Because litter is one of the most important variables in carrying wildfire in these systems (Andreu et al., 2012), the precision derived from survey data is encouraging. The least reliable predictions are for the hardwood group, but this vegetation group rarely experiences wildfires because it occurs in riparian and wetland areas in the Atlantic coastal plain.

The generally weak predictions associated with small twigs and branches likely results from the opposing forces controlling the dynamics of recruitment, such as tree mortality and breakage from storms (ice, wind, fire), pests and harvests (e.g., Aubrey et al., 2007; Campbell et al., 2008), and decay (Van Lear, 1996; Eaton and Sanchez, 2009). These materials are created by irregular canopy branch and stem breakage and they will decompose more quickly because of their small size. Tolhurst and Kelly (2003) have shown very large annual changes of 100–200% in recruitment of this component. The weak relationships, particularly differences in means among vegetation groups, may also be influenced by the use of local composite conversion for specific gravity that are not adjusted for either species or decay class (Harmon et al., 2008).

5.3. Recent fire history

Prescribed fire is often considered the cornerstone of FL management for the southeastern USA (Wade and Lunsford, 1989). The coefficients for years since last burn demonstrate the effect of prescribed fire in reducing litter and duff (Table 4). The shape of the relationship for the loblolly and longleaf pine groups is curvilinear. Fuel loading increases asymptotically with years since last prescribed burn (Fig. 2). This result has been observed in regional research experiments (Hough, 1978, 1982; McNab et al., 1978; Hanula and Wade, 2003) and elsewhere (Tolhurst and Kelly, 2003). The rapid recovery following the year since last burn supports the use of frequent prescribed fire at 2–3 year intervals to maintain low litter and duff biomass. The 1-, 10- and 100-h fuels are more complex to interpret because the coefficients for years

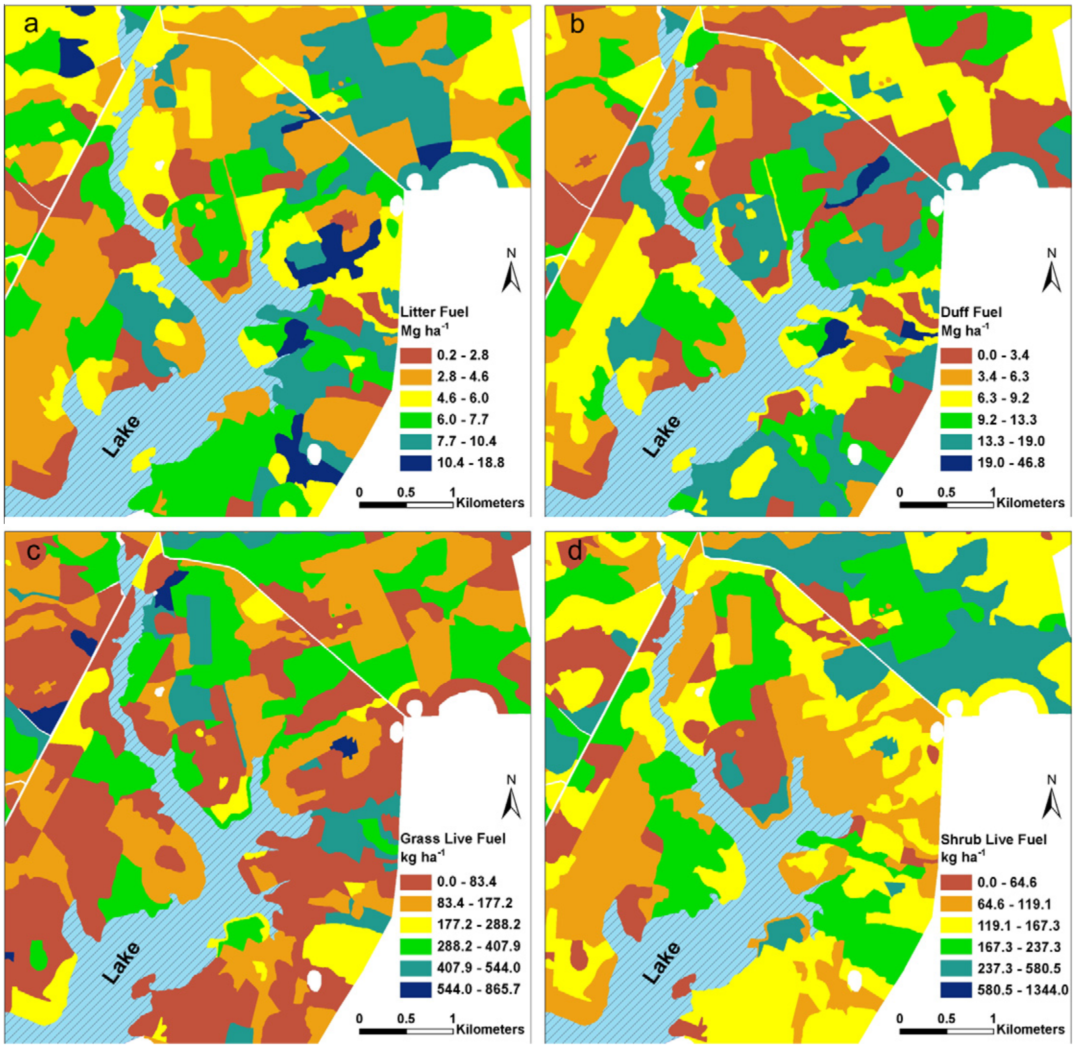

Fig. 3. Spatially distributed litter (a), duff (b), grass (c) and shrub (d) fuel loads as predicted stochastically from equations in Appendix A.

since last burn and number of burns are both positive and negative. The inconsistent results may be a consequence of processes discussed in Section 5.2., but may be partially attributed to whether the direct effect of fire on consumption in general balance the indirect effect of fire on mortality (Sullivan et al., 2003; Campbell et al., 2008). One-time survey data may be too infrequent to gain insights into the relationship between recent fire history and these FL components.

The lack of consistent effect of years since last burn on small trees, seedlings and shrubs (Table 4) agrees with published results (Glitzenstein et al., 1995; Brockway and Lewis, 1997; Kush et al., 1999). The results imply that live fuel components may interact with overstory–understory competitive effects (Slocum et al., 2003; Harrington, 2006) and fire intensity effects (Thaxton and Platt, 2006) in a complex manner. Dormant season prescribed fires are typically less effective in killing small trees or shrubs greater than 2.5 cm diameter due to generally lower intensity of these fires. Where significant, the number of burns is negatively related to biomass of these woody FL components. The curvilinear relationships (Fig. 2) identify that multiple prescribed fires are required to reduce woody biomass to low levels. In contrast, we interpret the positive effect of number of burns on forbs in the pine-hardwood as an improvement of general conditions for this component (Fig. 2h) (Glitzenstein et al., 2003). The observed effect may be limited to the 3 hardwood containing groups as a consequence of recent farming history that may have destroyed the native forbs cover in the upland pine stands (Imm and McLeod, 2005). The one observation that was not anticipated is the limited response of grasses to recent fire history. The dominant grass species are blue stems (*Andropogon* spp.) (Imm and McLeod, 2005). We expected that the grass component as a whole would show a consistent positive trend with number of burns. The high sensitivity of grass biomass to stand basal area is evident in longleaf pine (Fig. 2d) and loblolly pine (Appendix A). Basal area levels may be too high for many species of grass to respond to recent fire history as noted by Harrington (2006).

5.4. Implications for broader application and improving predictions and mapping

Plot-scale FL measurement systems can lead to more reliable fire hazard and fuel treatment effectiveness estimates (Ottmar et al., 2012). However, a plot-based fuels inventory is costly and will be applied only in situations where the benefit to cost ratio is justified, such as in the wildland–urban interface, or to validate treatment requirements or effectiveness. To reduce costs of generating high resolution FL data, we were able to successfully relate plot-scale measurements to stand attributes to impute stand-scale FL components, but the design did not address within stand patterns or variation. As a result, predicting the evolution of landscape FL and the effects on fire spread will remain challenging (Finney, 2001).

The analysis identifies two vegetation characteristics that may strongly influence the extent of large wildland fires in the southeastern USA. First, normal forest harvesting and silvicultural activities may have large influences on FL components through modifications of basal area, age distributions and competing vegetation at planting. Second, the resulting heterogeneity in FL components at scales of a few square kilometers can significantly break the continuity in hazardous FL sufficient to facilitate fire control depending upon the intensity (Finney, 2001; King et al., 2008). The resulting consequence is that coarse scale models of fire behavior (Hollingsworth et al., 2012) may be unsuitable for risk and treatment planning in ecological systems with complex processes that interact. The success, or lack thereof, in modeling and mapping FL components derived from our vegetation inventory data leads to broader implications for the southeastern USA and similar systems with ecologically complex and rapidly changing FL such as those found at the SRS. Although the data represent a limited ecological range, the management activities and land use are reflected in tens of millions of hectares in the southeastern USA, and therefore the basic quantitative relationships will probably hold.

Additional research is required on methodologies to optimize sampling and analysis. Given the relatively strong predictive values for basal area, age and site quality, as identified in this study, there is an opportunity to utilize airborne Light Detection and Ranging (LiDAR) technology along with other databases to create more precise spatial resolution of several surface FL variables (Reutebuch et al., 2005). Ground based LiDAR may also offer opportunities to better characterize surface live fuel structure and explain small scale fire behavior (Hiers et al., 2009; Loudermilk et al., 2009). The use of additional linkage variables, whether categorical or continuous (e.g., soil-landform properties, historical land use, and recent thinning history), may also improve the precision of the modeling.

We used locally derived bulk density conversion factors for litter and duff (Parresol, 2005) and composite parameters to compute 1-, 10-, 100- and 1000-h fuels from a local study by Scholl (1996). However, a recent meta-analysis by Harmon et al. (2008) suggests that significant improvement in the precision (20–30%) for these dead fuels is obtained by utilizing species or genera specific gravity values and decay class estimates for these fuels. Implementation of this method to improve precision will be challenging in regions where there is a large number of mixed species stands and rapid decay rates. Given the importance of the shrub layer and pine needle drape to extreme fire behavior (Andreu et al., 2012; Hiers et al., 2009), more reliable and efficient methods for quantifying these components are needed.

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Appendix A

See Table A.1.

Table A.1
Wildland fuel biomass (W) equations in Mg ha^{-1} for the Savannah River Site forest vegetation groups. Independent variables are: age in years (A); basal area in m^2 ha^{-1} (B); site index in meters, base age 50 years (S); years since last prescribed fire (Y); and number of times burned since 1971 or since stand establishment (N). The R^2 or coefficient of determination, P-value (probability) and the Root Mean Square Error (RMSE) are listed for each equation.

Forest vegetation group	Fuel component	Best predictive equation	R^2	RMSE	P-value
Loblolly pine	Litter	$\ln \hat{W}_{11} = -0.154 + 0.473 \ln B + 0.174 \ln Y$	0.423	0.4148	<.0001
	Duff	$\ln \hat{W}_{12} = -6.753 + 0.573 \ln A + 0.708 \ln B + 1.302 \ln S + 0.142 \ln Y$	0.531	0.7049	<.0001
	1-h	$\ln \hat{W}_{13} = -3.145 - 0.189 \ln A + 0.514 \ln B + 0.0961 \ln Y$	0.111	0.8406	<.0001
	10-h	$\ln \hat{W}_{14} = 0.00663 + 0.192 \ln B + 0.188 \ln N$	0.050	0.7373	0.0009
	100-h	$\ln \hat{W}_{15} = -5.548 + 0.444 \ln A - 0.417 \ln B + 1.825 \ln S - 0.0864 \ln Y$	0.145	0.9879	<.0001
	1000-h s	$\ln \hat{W}_{16} = 0.669 + 0.325 \ln A - 0.341 \ln B$	0.039	0.9770	0.1778
	1000-h r	$\ln \hat{W}_{17} = -0.681 + 0.332 \ln A$	0.032	1.2545	0.0237
	Small trees	$\ln \hat{W}_{18} = 1.127 - 0.695 \ln A + 1.138 \ln B - 0.195N$	0.190	1.3627	<.0001
	Seedlings	$\ln \hat{W}_{19} = -3.618 - 0.291 \ln B + 0.860 \ln S$	0.069	0.6692	<.0001
	Shrubs	$\ln \hat{W}_{1,10} = -1.498 - 0.171 \ln A + 0.0824 \ln Y$	0.036	0.9092	0.0074
	Vines	$\ln \hat{W}_{1,11} = -6.162 + 1.337 \ln S$	0.028	0.9194	0.0056
	Grasses	$\hat{W}_{1,12} = 0.205 \exp(-0.0759B + 0.0457S)$	0.328	0.1389	<.0001
	Forbs	$\ln \hat{W}_{1,13} = -2.531 - 0.775 \ln B$	0.144	1.1163	<.0001
Longleaf pine	Litter	$\ln \hat{W}_{21} = -1.485 + 0.553 \ln A + 0.372 \ln B + 0.171 \ln Y$	0.656	0.6276	<.0001
	Duff	$\ln \hat{W}_{22} = -9.228 + 1.340 \ln A + 1.957 \ln S$	0.578	0.9872	<.0001
	1-h	$\ln \hat{W}_{23} = 4.998 - 0.334 \ln A - 2.245 \ln S - 0.339 \ln N$	0.109	1.2124	0.0019
	10-h	$\ln \hat{W}_{24} = -0.208 + 0.284 \ln A - 0.167 \ln B - 0.173 \ln Y$	0.084	0.8547	0.0099
	100-h	$\ln \hat{W}_{25} = -0.184 + 0.553 \ln A - 0.551 nB$	0.106	1.0817	0.0007
	1000-h s	$\ln \hat{W}_{26} = -0.604 + 0.721 \ln A - 0.463 \ln B$	0.122	1.1975	0.0339
	1000-h r	$\ln \hat{W}_{27} = -3.328 - 0.176 \ln B + 1.313 \ln S$	0.056	1.2580	0.0893
	Small trees	$\hat{W}_{28} = 112.6 \exp(-0.0333A + 0.0606B - 0.118S + 0.00102Y^2)$	0.513	7.8472	<.0001
	Seedlings	$\hat{W}_{29} = 0.456 \exp(-0.0248B - 0.0215S + 0.00857Y)$	0.147	0.1170	<.0001

(continued on next page)

Table A.1 (*continued*)

Forest vegetation group	Fuel component	Best predictive equation	R^2	RMSE	*P*-value
	Shrubs	$\hat{W}_{2,10} = 2.191\exp(-0.00797A - 0.0945S)$	0.176	0.1308	<.0001
	Vines	$\hat{W}_{2,11} = 0.0346\exp(0.00947A + 0.0461S)$	0.052	0.1187	<.0001
	Grasses	$\hat{W}_{2,12} = 1.938\exp(-0.0164A - 0.0572B - 0.0469S)$	0.494	0.1487	<.0001
	Forbs	$\ln\hat{W}_{2,13} = 2.492 - 0.728\ln A - 1.508\ln S$	0.224	1.1805	<.0001
Slash pine	Litter	$\ln\hat{W}_{31} = 0.825 - 0.426\ln A + 0.865\ln B - 0.141\ln N$	0.620	0.2791	<.0001
	Duff	$\ln\hat{W}_{32} = -11.436 + 1.316\ln B + 3.000\ln S - 0.264\ln N$	0.645	0.5701	<.0001
	1-h	$\ln\hat{W}_{33} = -5.253 + 0.877\ln B$	0.119	1.1300	0.0080
	10-h	$\ln\hat{W}_{34} = 0.248 + 0.269\ln B - 0.242\ln Y$	0.172	0.6284	0.0055
	100-h	$\ln\hat{W}_{35} = 3.372 - 0.653\ln A - 0.1891nY$	0.142	0.7638	0.0146
	1000-h s	$\ln\hat{W}_{36} = -11.377 + 3.814\ln S$	0.131	0.9560	0.0457
	1000-h r	$\ln\hat{W}_{37} = -4.989 + 1.849\ln S$	0.027	0.7931	0.2738
	Small trees	$\hat{W}_{38} = 425.0\exp(-0.0302A + 0.0517B - 0.145S)$	0.261	8.7511	<.0001
	Seedlings	$\hat{W}_{39} = 1.266\exp(-0.0236A - 0.0287Y - 0.356N)$	0.397	0.0891	<.0001
	Shrubs	$\hat{W}_{3,10} = 12.831\exp(0.0158A - 0.108S - 0.0882Y - 1.214N)$	0.562	0.0690	<.0001
	Vines	$\hat{W}_{3,11} = 0.294\exp(0.0124B - 0.0349Y - 0.254N)$	0.138	0.1145	<.0001
	Grasses	$\hat{W}_{3,12} = 0.0165\exp(-0.0366A + 0.0292B + 0.121S - 0.0537Y - 0.281N)$	0.200	0.0526	<.0001
	Forbs	$\hat{W}_{3,13} = 0.216\exp(-0.0867A)$	0.931	0.0056	<.0001
Pine-hardwood	Litter	$\hat{W}_{41} = -2.633 - 49.019/A + 0.964S - 1.096/Y + 0.00884A \times B - 0.0107A \times S - 0.019B \times S$	0.658	1.6619	0.0041
	Duff	$\ln\hat{W}_{42} = -0.630 + 0.805\ln B + 0.451\ln N$	0.500	0.6683	0.0010
	1-h	$\ln\hat{W}_{43} = -6.896 + 0.408\ln A + 1.127\ln S$	0.247	0.7597	0.0590
	10-h	$\ln\hat{W}_{44} = -0.990 + 0.536\ln B$	0.316	0.6168	0.0052
	100-h	$\ln\hat{W}_{45} = -10.446 + 1.297\ln A - 0.737\ln B + 2.538\ln S$	0.627	0.7082	0.0003
	1000-h s	$\ln\hat{W}_{46} = -9.791 + 3.312\ln S - 0.523\ln N$	0.334	1.2256	0.1066
	1000-h r	$\ln\hat{W}_{47} = -6.782 - 0.434\ln B + 2.779\ln S - 0.373\ln N$	0.219	0.8335	0.5049
	Small trees	$\hat{W}_{48} = -8.174 + 0.993B + 44.638N - 1.748S \times N$	0.543	11.748	0.0016
	Seedlings	$\hat{W}_{49} = 0.0541\exp(-0.0716B + 0.100S)$	0.693	0.0667	<.0001
	Shrubs	$\hat{W}_{4,10} = 0.894\exp(-0.0164A - 0.0520S + 0.0152Y)$	0.574	0.0616	<.0001
	Vines	$\hat{W}_{4,11} = 0.173\exp(0.0141A - 0.0751B + 0.372N)$	0.598	0.0827	<.0001
	Grasses	$\hat{W}_{4,12} = 0.000071\exp(-0.0539A - 0.133B + 0.247S + 0.222Y + 1.444N)$	0.975	0.0332	<.0001
	Forbs	$\hat{W}_{4,13} = 1.327 \times 10^{-7}\exp(-0.336B + 0.553S + 0.122Y + 0.581N)$	0.920	0.0085	<.0001
Hardwood-Pine	Litter	$\hat{W}_{51} = -12.126 + 0.223A + 0.505Y - 0.00725A \times Y - 0.0346A \times N + 2.401B/S + 0.108B \times N$	0.459	1.7574	0.0370
	Duff	$\hat{W}_{52} = -32.821 + 0.773A + 1.117Y + 19.557N - 0.0213A \times Y - 0.390A \times N + 0.157Y \times N$	0.450	3.1611	0.0420
	1-h	$\ln\hat{W}_{53} = 0.820 - 0.707\ln B$	0.116	0.6262	0.0819
	10-h	$\ln\hat{W}_{54} = 7.559 - 0.498\ln A - 1.517\ln S$	0.242	0.3726	0.0361
	100-h	$\ln\hat{W}_{55} = 4.273 - 0.281\ln B - 0.788\ln S + 0.209\ln N$	0.080	0.7819	0.5825
	1000-h s	$\ln\hat{W}_{56} = 7.957 + 1.567\ln B - 3.694\ln S + 0.617\ln N$	0.793	0.4787	0.0009
	1000-h r	$\ln\hat{W}_{57} = -3.989 - 2.571\ln A + 4.899\ln S - 0.367\ln Y$	0.552	0.8479	0.0042
	Small trees	$\hat{W}_{58} = 16.102 + 3409.4/A - 4.535S + 0.0383A \times S$	0.394	14.947	0.0083
	Seedlings	$\hat{W}_{59} = 0.129\exp(0.0209B - 0.117N)$	0.270	0.0867	<.0001
	Shrubs	$\ln\hat{W}_{5,10} = 8.701 - 0.977\ln A - 0.608\ln B - 1.491\ln S$	0.103	1.1635	0.4853
	Vines	$\hat{W}_{5,11} = 0.124\exp(-0.0342B + 0.0365Y + 0.426N)$	0.297	0.1005	<.0001
	Grasses	$\hat{W}_{5,12} = 0.0152\exp(0.0992B)$	0.409	0.2124	<.0001
	Forbs	$\ln\hat{W}_{5,13} = -14.567 + 2.977\ln B + 0.484\ln N$	0.299	1.0955	0.0202
Hardwood	Litter	$\ln\hat{W}_{61} = 4.0111 + 0.128\ln B - 0.972\ln S + 0.115\ln Y$	0.080	0.6738	0.0405
	Duff	$\ln\hat{W}_{62} = 0.104 + 0.529\ln B$	0.233	0.6312	<.0001
	1-h	$\ln\hat{W}_{63} = -3.516 + 0.574\ln B$	0.253	0.7882	<.0001
	10-h	$\ln\hat{W}_{64} = -0.763 + 0.405\ln B + 0.258\ln N$	0.164	0.7633	0.0001
	100-h	$\ln\hat{W}_{65} = -2.260 - 0.428\ln A + 0.333\ln B + 1.037\ln S + 0.257\ln N$	0.116	0.9235	0.0154
	1000-h s	$\ln\hat{W}_{66} = -1.644 - 0.307\ln B + 1.078\ln S$	0.026	1.1190	0.5756
	1000-h r	$\ln\hat{W}_{67} = -1.244 + 0.991\ln A - 0.461\ln B - 0.291\ln Y - 0.937\ln N$	0.186	1.1755	0.0126
	Small trees	$\hat{W}_{68} = 15.338 - 0.303A + 20.197B/S$	0.193	12.315	<.0001
	Seedlings	$\hat{W}_{69} = 0.128\exp(0.00281B + 0.0282S - 0.0102Y - 0.113N)$	0.078	0.1127	<.0001
	Shrubs	$\ln\hat{W}_{6,10} = 1.697 - 0.286\ln A + 0.259\ln B - 1.039\ln S - 0.532\ln N$	0.111	0.9444	0.0236
	Vines	$\ln\hat{W}_{6,11} = -7.831 + 0.177\ln B + 1.663\ln S$	0.169	0.8444	<.0001
	Grasses	$\ln\hat{W}_{6,12} = -7.021 - 0.314\ln B + 1.910\ln S - 0.392\ln N$	0.153	1.2123	0.0014
	Forbs	$\hat{W}_{6,13} = 6.925 \times 10^{-9}\exp(-0.00761A + 0.277B + 0.152Y + 1.734N)$	0.481	0.0251	<.0001

Appendix B

See Table B.1.

Table B.1
Logistic regressions to predict presence/absence of the 1000 h fuel.

Forest vegetation group	Category	Logistic equation	Cut-off probability
Loblolly pine	Sound	$\hat{p}_{11} = [1 + \exp(-0.999 + 0.0294A - 0.0312B)]^{-1}$	0.3
Longleaf pine	Sound	$\hat{p}_{21} = [1 + \exp(-3.329 + 0.0193A - 0.0462B + 0.129S)]^{-1}$	0.4
Slash pine	Sound	$\hat{p}_{31} = [1 + \exp(0.000791 + 0.0278A - 0.0347B - 0.0243Y)]^{-1}$	0.5
Pine-hardwood	Sound	$\hat{p}_{41} = [1 + \exp(-5.768 + 0.0475A + 0.171Y + 1.378N)]^{-1}$	0.5
Hardwood-pine	Sound	$\hat{p}_{51} = [1 + \exp(2.343 - 0.0849B)]^{-1}$	0.45
Hardwood	Sound	$\hat{p}_{61} = [1 + \exp(-2.455 + 0.0710B + 0.352N)]^{-1}$	0.45
Loblolly pine	Rotten	$\hat{p}_{12} = [1 + \exp(-2.0540 + 0.0243A - 0.0279B + 0.0897S)]^{-1}$	0.5
Longleaf pine	Rotten	$\hat{p}_{22} = [1 + \exp(-2.309 + 0.0260A - 0.0514B + 0.0926S + 0.361N)]^{-1}$	0.55
Slash pine	Rotten	No relationship	
Pine-hardwood	Rotten	$\hat{p}_{42} = [1 + \exp(-15.590 - 0.256B + 0.315S + 0.441Y + 5.082N)]^{-1}$	0.5
Hardwood-pine	Rotten	$\hat{p}_{52} = [1 + \exp(-0.478 + 0.0536A - 0.0762B + 1.215N)]^{-1}$	0.75
Hardwood	Rotten	$\hat{p}_{62} = [1 + \exp(-1.972 + 0.0161A + 0.0558S + 0.0177Y)]^{-1}$	0.6

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