Forest Ecology and Management 273 (2012) 17–28

Contents lists available at SciVerse ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Fuel treatment effectiveness in forests of the upper Atlantic Coastal Plain – An evaluation at two spatial scales ☆

Roger D. Ottmar [a,*], Susan J. Prichard [b]

[a] US Forest Service, Pacific Northwest Research Station, Seattle, WA, USA
[b] University of Washington, School of Forest Resources, Seattle, WA, USA

ARTICLE INFO

Article history:
Available online 10 November 2011

Keywords:
Fuel treatment effectiveness
Fire behavior
Fire hazard
Fuel Characteristic Classification System
Southeastern United States
Longleaf pine

ABSTRACT

Fuel treatment effectiveness in Southern forests has been demonstrated using fire behavior modeling and observations of reduced wildfire area and tree damage. However, assessments of treatment effectiveness may be improved with a more rigorous accounting of the fuel characteristics. We present two case studies to introduce a relatively new approach to characterizing fuels and predicting potential fire behavior, fuel consumption, and emissions in Southern forests using the Fuel Characteristic Classification System (FCCS) and Consume. The first case study provides fine-scale (<100 ha) examples of fuel treatments (prescribed fire, mechanical thinning, mastication, and herbicide treatment) and their potential effect on predicted fire behavior and effects on measured treatment units. The second case study evaluates potential fire behavior across a managed forest landscape (74,000 ha) in the upper Atlantic Coastal Plain, South Carolina.

Results from the fine-scale assessment indicate that fuel treatments reduce reaction intensity, rate of spread, and flamelength by up to 58%, 57%, and 63%, respectively. Fuel loading of strata that control surface fire behavior (i.e., shrubs, grasses, fine woody fuels, and litter) range from 32.0 Mg ha^{-1} in the thinned, untreated unit to 8.5 Mg ha^{-1} in the unthinned unit treated with herbicides and prescribed fire. Based on model predictions, up to 80% less fuel would be consumed with concomitant reduction in emissions during a wildfire occurring in the treated units compared to the untreated unit.

Assessments of potential fire behavior across the study area indicate that overall hazard is low to moderate for this forested landscape. However, localized areas of high surface fire and crown fire potential were identified. Plot- and stand-based modeling both suggest that the potential for high to extreme fire behavior exists for this landscape. Combined, the two case studies highlight the ability of the FCCS to represent measured fuel characteristics and predict differences in potential fire behavior resulting from fuel treatments. Even small differences in fuel characteristics resulting from fuel treatments or site variation could be detected, allowing the effects of both ecological processes and management actions to be quantified.

Published by Elsevier B.V.

1. Introduction

Fire is an integral process in pine forests and savannas of the southeastern United States (Outcalt and Sheffield, 1996; Brockway et al., 2005). Historically, the fire regime was characterized by frequent (2–5 years), low intensity surface fires (Waldrop et al., 1992; Frost, 1993), and much of the Southern landscape was dominated by longleaf pine (*Pinus palustris*) forests and savannas with an open understory rich in herbaceous plant species diversity (van Lear et al., 2005; Haywood, 2007). A combination of factors including cessation of aboriginal burning, fire suppression, commercial pine plantations, and habitat fragmentation have not only reduced the extent of longleaf pine (*Pinus palustris*) forests from an estimated 15.4 million ha to <0.5 million ha (Noss, 1989; Outcalt and Sheffield, 1996; Brockway et al., 2005) but also increased fire hazard. Many Southern pine forests are extremely productive due to abundant moisture, warm temperatures, a long growing season, and the ability of many species to resprout following disturbance (Tian et al., 2010). During a single year, these forests can add tens of Mg per hectare of shrubs grass, woody debris, litter, and duff biomass. In the absence of frequent fire, even for as few as 10 years, dense understories of hardwoods and shrubs rapidly develop and increase the potential for high intensity surface and crown fires (Brose and Wade, 2002; Waldrop et al., 2009).

Frequent prescribed understory burns are commonly used to restore and maintain an open understory of pine forests under the historic fire regime. An expanding wildland urban interface and fragmented landscape of forest and agricultural fields creates

---

☆ *Contribution to a Special Issue:* Ecological and Management Factors Influencing Observed Hazardous Fuels and Predicted Wildfire Attributes in the Southeast United States.

* Corresponding author. Tel.: +1 206 732 7826.
E-mail address: rottmar@fs.fed.us (R.D. Ottmar).

0378-1127/$ - see front matter Published by Elsevier B.V.
doi:10.1016/j.foreco.2011.09.040

challenges for prescribed burn programs, including risk of escape to adjacent lands and conflicts over air pollutant emissions (Theobald and Romme, 2007; Marshall et al., 2008; Zhang et al., 2008). Even where prescribed fire is still possible, many Southern forests have missed several burn rotations and now have hazardous fuel accumulations that may require a combination of mechanical, herbicide and prescribed burning treatments to create conditions in which prescribed burning can be safely initiated (Brockway and Lewis, 1997; Heuberger and Putz, 2003; Brockway et al., 2009).

Fire hazard reduction and savanna habitat restoration are often compatible management objectives in Southern pine forests, particularly in areas prioritized to restore the endangered red-cockaded woodpecker (RCW, *Picoides borealis*) (Zwicker and Walters, 1999; Brockway et al., 2005). These forests are frequently treated to reduce surface fuels, restore open, grass-dominated forest understories and provide recruitment opportunities for Southern yellow pine species, which require mineral soil seedbeds for establishment (Brockway et al., 2005; Marshall et al., 2008). Treatments serve to mitigate potential fire behavior, reduce susceptibility to bark beetle outbreaks (Fettig et al., 2007), and improve wildlife habitat.

Several studies have investigated the effects of common fuel treatments applied to Southern pine forests and the relative effectiveness of individual treatments and treatment combinations in (1) modifying vegetation structure and composition and (2) reducing predicted or actual wildfire behavior. Common treatments include prescribed fire, mechanical thinning, mastication (chipping and shredding), and herbicide treatment, and are reviewed in the following sections.

1.1. Prescribed burning

Studies of the effectiveness of frequent prescribed fire in reducing shrubs and midstory hardwoods are in close agreement and show empirically that frequent prescribed fire (every 2–5 years) is an effective strategy for maintaining open understories and reducing fire hazard. Compared to dormant season fires, spring and growing-season fires are more effective at reducing midstory hardwoods, thinning small diameter pines, and creating open understory conditions (Ferguson, 1961; Waldrop et al., 1987; Wade, 1993; Glitzenstein et al., 1995; Haywood, 2007). Hardwood and shrub species are more likely to resprout following a dormant season versus growing season burns (Drewa et al., 2002). Dormant season burns on an annual or 2 year rotation are also effective at reducing midstory hardwoods and shrubs (Brockway and Lewis, 1997; Provencher et al., 2001; Sparks et al., 2002; Glitzenstein et al., 2003; Cox et al., 2004; Haywood, 2007; Brockway et al., 2009).

Regardless of burn season, prescribed burning every 2–5 years is considered the most effective management strategy for reducing potential wildfire behavior and post-fire pine mortality (Moore et al., 1955; Davis and Cooper, 1963; Sackett, 1975; Haywood, 2009; Outcalt and Wade, 2004; Waldrop et al., 2009). Brose and Wade (2002) used BEHAVE (Andrews, 1986) to evaluate potential surface fire behavior in pine flatwood forests that were thinned, treated with herbicide, or prescribed burned in the dormant season. They conclude that dormant season burning every 3–5 years is the most effective treatment in reducing predicted surface fire behavior. Waldrop et al. (2009) report similar findings from fire behavior simulations following prescribed fire and other fuel treatments. Due to vigorous sprouting and regrowth of vegetation as well as rapid litter accumulations, frequent burning is required to maintain low fire hazard in Southern forests (Brose and Wade, 2002; Waldrop et al., 2009). Martin (1988) evaluated wildfire incidence in large wildfires across national forests in the southeastern United States in 1985 and reports that incidence of wildfires was significantly lower in areas that had been prescribed burned 2 years previously. Similarly, Haywood (2009) reports high pine mortality following a wildfire in untreated units and units treated with herbicide relative to dormant, growing- and spring-season prescribed burn units.

1.2. Thinning and mastication

Commercial thinning and mastication (i.e., chipping and shredding) are integral components of forest management and pine savanna restoration in the southeastern United States. Due to fire exclusion or long intervals between prescribed burns, many Southern pine forests require thinning treatment to reduce tree densities and ladder fuels (Brockway et al., 2005; Marshall et al., 2008; Waldrop et al., 2009). In a study that compares thinning, herbicide treatment, and spring burning treatments in a sandhill site in northern Florida, Provencher et al. (2001) conclude that although not effective alone in reducing midstory hardwoods, mechanical thinning can be used for rapid removal of vegetation and should be followed by frequent fire and/or herbicide treatments. A similar conclusion is presented in a study by Brockway et al. (2009) in which a midstory treatment effectively reduced stand density and ladder fuels but sprouting shrubs and hardwoods quickly recovered in the mulch-only treatment.

Mechanical thinning treatments are generally effective at reducing crown densities and ladder fuels and may reduce the likelihood of crown fire initiation and spread (Brose and Wade, 2002; Waldrop et al., 2009). However, treatment of surface fuels in conjunction with thinning would be necessary to reduce potential surface fire behavior (Agee and Skinner, 2005; Peterson et al., 2005). Glitzenstein et al. (2006) evaluate changes in fuels and fire behavior in chipped and unchipped treatments and report that chipping reduced total fuel depth and resulted in lower observed and predicted fire behavior than unchipped plots. However, they note that fire behavior fuel models in their modeling approach did not accurately characterize the vertical arrangement of fuels. Depending on fire weather conditions, fuels that have been chipped or shredded may represent a short-term increase in surface fire behavior and fire duration (Glitzenstein et al. 2006; Reiner et al., 2009). Southern pine species are well-adapted to high levels of crown scorch but are susceptible to mortality from root damage in long-duration surface fires (Brose and Wade, 2002).

1.3. Herbicide application

Herbicide treatments are effective at reducing shrub and hardwood species and improving recruitment and growth opportunities for longleaf pine and grasses and other herbaceous species (Brockway and Outcalt, 2000; Provencher et al., 2001; Freeman and Jose, 2009). Provencher et al. (2001) report that the greatest reduction of understory oak species was achieved with application of herbicide followed by a fuel reduction fire. In a study in longleaf pine forests, Gagnon and Jack (2004) report that herbicides effectively reduced midstory hardwoods but that woody biomass and litter was retained in these treatments and in the absence of fire, would likely result in increased surface fire behavior potential over time.

Herbicides are generally used in conjunction with prescribed fire to reduce potential fire behavior and effects. In the short term, herbicide applications result in an increase in standing dead vegetation before it falls and begins to decompose. For example, Outcalt and Wade (2004) note that areas treated with herbicides within 2 years of a wildfire event were not effective at reducing postfire tree mortality. Haywood (2009) also found that pine mortality following a wildfire in treated longleaf pine units was high in herbicide-only treatments as compared to prescribed burn treatments. Similar to mastication treatments, herbicide does not reduce litter and organic soil accumulations and may predispose pine forests to high mortality from surface fires with long fire residence times (Brose and Wade, 2002).

In summary, frequent prescribed fire is consistently the single-most effective treatment option for reducing hazardous fuels in Southern pine forests and reducing fire hazard. Successful applications require multiple fires to create and maintain open understory growing conditions and may require a combination of treatments including midstory biomass removal, mastication, and/or herbicide application to restore forest structure. The effectiveness of fuel treatments has been demonstrated using the Rothermel (1972) spread model (Brose and Wade, 2002; Glitzenstein et al., 2006; Waldrop et al., 2009), however fuel models, which are input into the spread model, are limited in their ability to characterize the vertical arrangement and spatial variability of fuelbeds (Glitzenstein et al., 2006).

In this paper, we evaluate the utility of the Fuel Characteristic Classification System (FCCS) (Ottmar et al., 2007) and Consume (Ottmar et al., 2005) for characterizing fuels and predicting potential fire behavior, fuel consumption, and emissions in Southern pine forests. The FCCS represents differences in fuel characteristics under various forest management scenarios (Ottmar et al., 2007) and records realistic fuelbed information in six distinct strata including the canopy (trees, snags, and ladder fuels), shrubs, non-woody (grasses and forbs), woody, (downed woody debris, stumps, and piles), litter-lichen-moss (Oi soil horizon), and duff (Oe and Oa soil horizons) (Ottmar et al., 2007). Each stratum is further divided into categories and subcategories, allowing the system to account for specific fuelbed characteristics such as the percentage of live versus dead biomass, relative cover of shrub and grass species, occurrence of needle drape and ladder fuels, and the depth, loading, and percent cover of fine woody material (0–7.6 cm) and litter. The FCCS calculates surface fire behavior, crown fire, and available fuel potentials scaled on an index from 0 to 9 (Sandberg et al., 2007a) and predicts surface fire behavior including reaction intensity (kW m^{-2}), flame length (m), and rate of spread (m min^{-1}) (Sandberg et al., 2007b). Consume is a physical- and empirical-based model that predicts fuel consumption and emissions generated from wildland fire from such variables as fuel loading, fuel moisture, and other environmental factors (Ottmar et al., 2005). It is used as a decision-making tool and is directly linked to the FCCS. FCCS and Consume are used in case studies focusing on predictions of fire behavior and effects for a managed forest landscape in the upper Atlantic Coastal Plain, South Carolina. Results of this analysis will assist fire and fuels managers with decision making about effective treatments and resource allocation for reducing wildfire hazard and smoke emissions.

2. Study area

The case studies were conducted on the Savannah River Site (SRS), South Carolina. The SRS is a US Department of Energy facility and contains approximately 74,000 ha of forestland, composed mostly of actively managed pine and mixed pine and hardwood stands (Table 1). Over half of the land base is forested with stands of loblolly pine (*Pinus taeda*), longleaf pine, and slash pine (*Pinus echinata*) that were planted or naturally regenerated in old agricultural fields after the SRS was established in 1951. Approximately 50,000 ha of pine forests are regularly thinned and treated with prescribed fire to reduce fire hazard to adjacent lands and to protect critical infrastructure and operations on the site. Annually, around 2000 ha are thinned each year, and over 10,000 ha are currently broadcast burned (Kilgo and Blake, 2005), herbicide treated, and masticated. Approximately 28,000 ha of the existing stands of pine are managed with fire and mechanical thinning operations to restore habitat for the red-cockaded woodpecker. Hardwood forests are generally confined to riparian corridors and are composed of a mix of deciduous and evergreen species common to the Atlantic Coastal Plain, including, *Acer* spp., *Betula* spp., *Carya* spp., *Fagus grandifolia*, *Fraxinus* spp., *Liquidambar styraciflua*, *Nyssa* spp., *Quercus* spp., and *Ulmus* spp. (Kilgo and Blake 2005).

3. Study 1: Evaluating fuel treatment options in Atlantic Plain forests

The objective of this case study was to use the FCCS and Consume to evaluate fire behavior, fuel consumption, and emissions following fuel treatments that are applied to the managed Southern pine forests of the SRS. FCCS is a relatively new system (Ottmar et al., 2007), and this case study was developed to evaluate how well it captures differences in common fuel treatments using internal fire behavior prediction models. The selected fuel treatments included unthinned and thinned forest sites with one or more of the following treatments: (1) no treatment, (2) herbicide, (3) prescribed fire, and (4) chip and shred. Our analysis use inventoried fuels data and predicts potential fire behavior using the FCCS. Fuel consumption and emissions are modeled with Consume.

3.1. Methods

Managers at SRS compiled a list of 13 untreated and recently treated units available for inventory and fire hazard assessment at the time of this study. No replications were conducted and no units were followed through time due to time and funding constraints. Treatments included herbicide application (foliar and soil activated chemical broadcast sprayed from a truck mounted sprayer), chip and shred (mastication), and prescribed fire (hand or helicopter ignited using a strip head fire firing pattern between November and March), and a combination of these treatments. The length of time since last treatment ranged from 5 months for the unthinned unit treated with herbicide and prescribed fire to 36 months for the unthinned, untreated unit to (Table 1). Fuels were inventoried by systematically positioning 10 plots across each of the 13 units. Two 22-m fuel transect lines were established radiating from the plot center at randomly selected azimuths. The 0–0.63, 0.63–2.54, >2.54 cm diameter woody fuels (Brown, 1974), and vegetation cover by category (Canfield, 1941) were measured between 0–1, 0–3, 0–22, and 0–22 m along each transect. Litter and duff depths and height of shrubs, grasses, and seedlings, and fine fuel high particle height (Brown, 1974) were measured at 5, 10, 15, 20, and 25 m along each fuel transect. The point-quarter method (Cottam and Curtis, 1956) was used to assess overstory, mid-story, and understory trees for diameter, density, height to live crown, tree height, and percentage cover. Finally, ladder fuel and needle drape were visually estimated to be present or not present in enough mass and continuity to affect fire behavior.

Inventoried plot data were summarized and used to construct FCCS fuelbeds to represent each unit. Surface fire behavior was calculated using FCCS environmental variables that included (1) no slope, (2) 6.4-km h^{-1} mid flame wind speed, (3) dry weight fuel moistures by woody fuel time lag class: 1-h (5%), 10-h (6%) 100-h, (11%), and 1000-h (15%), (4) 30% duff moisture content, and (5) 113% live shrub and herbaceous vegetation. We selected this environmental scenario to represent a reasonable comparison of modeled fire behavior between treatments during a late winter (dormant season) wildfire event and be consistent with analysis from Andreu et al. (2012). FCCS fuelbeds were imported into Consume to predict fuel consumption and emissions under the same environmental scenario used in FCCS.

Table 1
Time since treatment, total aboveground loading and predicted consumption, PM 2.5 emissions, surface fire reaction intensity, rate of spread, and flame length for each treatment (NT = no treatment; Herb = herbicide; C&S = chip and shred; Rx = prescribed fire).

Treatment	Time since treatment (months)	Total above ground loading (Mg ha^{-1})	Consumption (Mg ha^{-1})	Emissions PM 2.5 (Mg ha^{-1})	Reaction intensity (kW m^{-2})	Rate of spread (m min^{-1})	Flame length (m)
Unthinned							
NT	36	441.61	18.90	0.20	824.10	1.40	2.70
Herb	15	130.02	23.00	0.29	398.80	0.80	1.60
C&S 1	8	85.18	7.20	0.04	396.40	0.90	1.70
C&S 2	6	78.46	6.10	0.04	362.30	0.70	1.50
C&S/Rx	12	91.91	12.10	0.09	401.70	0.90	2.10
Herb/Rx	5	62.77	3.70	0.02	392.20	0.80	1.50
Thinned							
NT 1	24	145.71	17.60	0.11	670.80	1.30	1.90
NT 2	20	121.05	14.00	0.11	455.20	0.90	1.60
Rx 1	8	98.63	9.70	0.07	384.50	0.80	1.40
Rx 2	8	141.23	8.50	0.07	344.10	0.60	1.00
C&S 1	6	80.70	7.80	0.04	383.70	0.80	1.40
C&S 2	6	100.88	6.10	0.04	375.00	0.70	1.40
Herb/C&S/Rx	8	143.47	15.70	0.16	366.10	0.80	1.90

3.2. Results and discussion

Total fuel loading including trees, shrubs, grasses, woody debris, litter, and duff is highest at 441.6 Mg ha^{-1} on the unthinned, untreated unit and lowest at 62.8 Mg ha^{-1} on the unthinned unit treated with herbicides and prescribed fire (Table 1). Because tree boles are often the largest contributor of aboveground biomass, thinned stands generally have lower total biomass than unthinned stands. However, the unthinned unit treated with herbicides and prescribed fire actually has the lowest reported biomass, due to small tree diameters on this particular unit.

Fuel loading of strata that influence surface fire behavior (i.e., shrubs, grasses, fine woody fuels, and litter) ranges from 32.0 Mg ha^{-1} in the thinned unit without surface fuel treatment (NT1) to 8.5 Mg ha^{-1} in the unthinned unit treated with herbicides and prescribed fire (Table 2). As would be expected, surface fuel loads are substantially higher in the untreated units than the treated units. These fuelbed components often rapidly increase over time in Southern forests due to high site productivity, which results in a short length of effectiveness for all surface fuel treatments (Waldrop et al., 2009).

Predicted surface fire behavior, including reaction intensity (kW m^{-2}), flame length (m), and rate of spread (m min^{-1}), are generally highest in the unthinned and thinned units without surface fuel treatment (Fig. 1). Surface fuels on these units had not been treated for at least 20–36 months (Table 1), and fuel accumulations during this time period resulted in higher predicted surface fire behavior. This indicates fuel treatments (chipping and shredding, prescribed burning, or combined herbicide with treatment) that target the litter, shrub, and fine woody, reduce these fire behavior values.

Results indicate fuel treatments can reduce reaction intensity, rate of spread, and flamelength by up to 58%, 57%, and 63%, respectively (Table 1). Since litter is often the largest contributor to reaction intensity (Fig. 1a), reducing or eliminating this fuelbed component will reduce this surface fire behavior variable. Predicted flame lengths are relatively low and controllable even for the untreated units due to the frequent application of fire and averaged 2.1 m for untreated units and 1.6 m for the treated units. Since flamelength is a function of reaction intensity, rate of spread, and residence time (Sandberg et al., 2007b), treatments that reduce litter will reduce flame length. However, litter fall can rapidly increase resulting in flame lengths above 4 feet, which often can create control problems and reducing treatment effectiveness (Marshall et al., 2008; Waldrop et al., 2009).

Time since surface fuel treatment was variable between sites ranging from 5 to 15 months, and two treatments in particular had longer intervals between treatment and sampling, including the unthinned-herbicide unit, which was sampled 15 months post-treatment, and the unthinned chip and shred/prescribed burn unit, which was sampled 12 months post-treatment (Table 1). In both units, shrub, woody fuel, and litter accumulations are high

Table 2
Fuel loading of the grass, shrub, fine woody fuel, and litter by treatment (NT = no treatment; Herb = herbicide; C&S = chip and shred; Rx = prescribed fire).

Treatment	Total loading (Mg ha^{-1})	Total grass loading (Mg ha^{-1})	Total shrub loading (Mg ha^{-1})	Total fine woody loading (Mg ha^{-1})	Total litter loading (Mg ha^{-1})
Unthinned					
NT	29.78	0.05	10.25	5.24	14.24
Herb	20.45	0.02	3.82	8.05	8.56
C&S 1	14.43	0.00	0.00	4.86	9.57
C&S 2	11.63	0.00	0.00	4.37	7.25
C&S/Rx	19.72	0.02	3.24	5.15	11.31
Herb/Rx	8.53	0.05	0.00	2.39	6.09
Thinned					
NT 1	32.03	0.00	0.05	17.18	14.79
NT 2	21.41	0.05	0.29	10.61	10.47
Rx 1	16.73	0.02	0.00	11.48	5.22
Rx 2	15.40	0.00	0.00	10.18	5.22
C&S 1	14.31	0.00	0.00	6.48	7.83
C&S 2	11.07	0.00	0.00	4.98	6.09
Herb/C&S/Rx	15.73	0.02	0.00	7.01	8.70

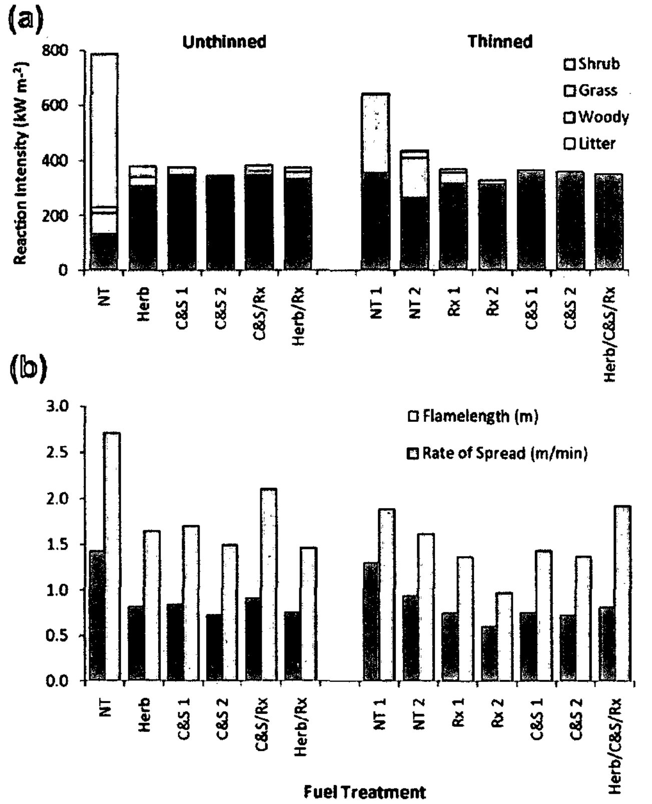

Fig. 1. Predicted surface fire (a) reaction intensity (kW m^{-2}) by surface fuel stratum, (b) flame length (m), and rate of spread (m min^{-1}) by treatment (NT = no treatment; Herb = herbicide; C&S = chip and shred; Rx = prescribed fire).

(Table 2) and likely contributed to high predictions of surface fire behavior (Fig. 1). These results suggest that shrubs, small woody fuels and litter should be the components targeted to effectively reduce fire behavior. Andreu et al. (2012) corroborate these findings in a more comprehensive analysis of fuelbed variables that contribute to surface fire behavior.

Predicted crown fire potential, on a scale of 0–9, is low with index values of 1–3 across all units (Fig. 2). The study area is under active forest management and all units surveyed had been treated or thinned within the past three years resulting in the low crown fire index values. Many fuel treatments resulted in lower crown fire potentials (1–2 vs. 3 in untreated sites), likely because the treatment reduced ladder fuels and/or the surface fire behavior.

Fuel consumption predicted by Consume ranges from 23.0 Mg ha^{-1} in the unthinned herbicide treated unit to 3.7 Mg ha^{-1} on the unthinned herbicide and prescribed burned unit (Table 1). Consumption is high in a majority of the untreated units since surface fuels had not been treated and more fuels were available to consume under constant fuel moisture scenarios. An exception is the unthinned, herbicide-treated unit in which more woody fuel had accumulated since the last treatment and was available for consumption. This anomaly may be a result of stand history or randomly selecting units for the study and not following individual units through the treatment cycles with permanent inventory plots.

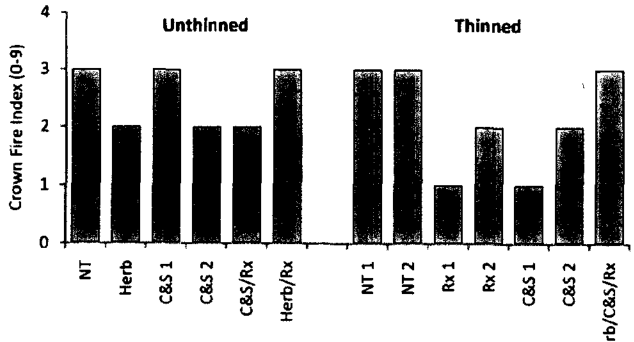

Fig. 2. Predicted crown fire potential index (0–9) by treatment (NT = no treatment; Herb = herbicide; C&S = chip and shred; Rx = prescribed fire).

Predicted PM$_{2.5}$ emissions ranges from 0.29 Mg ha^{-1} in the unthinned unit with herbicide application to 0.02 Mg ha^{-1} on the unthinned unit treated with herbicides and prescribed fire (Table 1). This is similar to the fuel consumption results since the amount of PM$_{2.5}$ emissions generated is correlated with the amount of fuel consumed (Ottmar et al., 2009).

3.3. Management implications

Comparison of treatment effectiveness using the FCCS closely reflects findings from other studies (Waldrop et al., 1987, 2009; Brose and Wade, 2002; Outcalt and Wade, 2004; Glitzenstein et al., 2006). Frequent treatment of surface fuels through prescribed burning, herbicide treatment and chipping and shredding or a combination with prescribed fire is often necessary to reduce hazardous fuel accumulations of surface fuels, including shrubs, grasses, fine woody debris, and litter in Southern pine forests. Single applications aimed at fuel reductions may not be effective if applied alone, if intensity of treatment is not sufficient to alter structure, or if not repeated (Sackett, 1975; Waldrop et al., 2009). Although not replicated to allow for statistical analysis of treatment differences, this case study indicates that the FCCS is capable of reflecting relatively small differences in fuel structure and loading in predicted fire behavior. The system uses realistic fuelbed strata, categories, and subcategory inputs and therefore has a high sensitivity to differences in the canopy and surface fuels accounting for variation in fuel structure and loading associated with fuel treatment activities. Furthermore, the realistic fuelbeds associated with the FCCS are directly compatible with Consume and other fire effects models (Ottmar et al., 2007).

Fuelbeds are readily imported into Consume to make fuel consumption and emission production estimates for further evaluation of treatment options with regard to fire effects and ecological consequences. According to Consume model outputs, up to 67% less fuel would be consumed with concomitant reduction in emissions during a wildfire occurring in the treated units as compared to the untreated unit, but such impressive reductions begin to erode within a matter of months and disappear altogether in a few years as limbs and litter accumulates and shrubs resprout (Waldrop et al., 2009). Use of FCCS and Consume to represent specific stand-level fuel treatments will assist managers of Southern pine forests in determining which fuel treatments are most effective and how best to allocate resources for wildfire hazard reduction, meeting resource objectives, reducing potential pollutant emissions, and restoring habitat.

4. Study 2: Landscape analysis of surface and crown fire potential in upper Atlantic Coastal Plain forests

Fire managers in Southern pine forests typically use traditional fire behavior fuel models and the Rothermel (1972) fire spread model in combination with crown fire modeling to predict fire behavior in prescribed and wildland fires. Regional assessment tools including LANDFIRE and the Southern Wildfire Risk Assessment (SWRA) provide coarse-scale (30-m), geospatial layers of fuels and fire hazard (Buckley et al., 2006; Rollins, 2009). Both products rely on satellite imagery coupled with limited field data to interpret the vegetation and assign fire behavior fuel models (Anderson, 1982; Scott and Burgan, 2005) and canopy layer information. They are intended for broad-scale assessments and are not necessarily applicable at the scale of most treatment units (<50 ha). Because surface and canopy fuels in managed forests can be highly variable even within similar vegetation types (Hiers et al. 2009), fuel models assigned by imagery can be too general to make site-specific fire behavior predictions (Arroyo et al., 2008). In addition, as inputs to the Rothermel spread model (Rothermel, 1972), surface fire behavior fuel models assume that surface fuels are part of a single, homogeneous layer and do not necessarily capture the inherent heterogeneity of managed surface fuels under a variety of treatments.

In this study, we evaluated the applicability of FCCS to predictions of fire behavior across the study area. The FCCS calculates a static fire behavior prediction based on input fuelbed characteristics and does not model fire spread across landscapes. The objectives of this study were to determine if field-based FCCS fuelbeds could be scaled to a broad spatial scale and to compare our plot-based estimates to predictions using traditional modeling techniques (Hollingsworth et al., 2012). We use three modeling approaches to characterize fuels and potential fire behavior across the SRS under a environmental scenario representing winter wildfire burning conditions: (1) a plot-based analysis using fuelbeds created from inventory plots regularly sampled across the study area, (2) stand-based mapping of potential fire behavior using fuelbeds representative of major forest types and age classes, and (3) stand-based mapping using a statistical imputation method. Finally, we joined FCCS inventory plots to modeled landscapes of surface fire behavior using LANDFIRE and the Southern Wildland Fire Risk Assessment (SWRA) and compared fire behavior estimates from observed measurements to these modeled landscapes.

4.1. Methods

We used three modeling approaches to characterize fuels and potential fire behavior across the SRS. The first approach was to model potential fire behavior using the 624 fuelbeds created from forest inventory plots. Vegetation and fuel characteristics were collected from 624 forest inventory plots in late 1999 and through early 2002 (Parresol et al., 2012a). Inventory data were entered to create a fuelbed to represent each inventory plot, and FCCS was used to predict surface fire behavior and a crown fire behavior index for each plot. This analysis yields a point-based FCCS prediction of potential fire behavior for each plot location.

The second approach was to map potential fire behavior across the study area using representative fuelbeds based on major forest type and age classes. Over 6300 stands were delineated from previous aerial photo and ground interpretation and assigned a forest type and age class. Inventory plot data were summarized to create a representative fuelbed for each major forest type and age class category using mean values for each representative fuelbed (Andreu et al., 2012). We calculated potential fire behavior and assigned fire behavior outputs to delineated stands using their stand type and age class (Fig. 3).

The final approach was to model potential fire behavior for the 6329 stands using statistically imputed plot-based fuels data (Parresol et al., 2012a). Parresol et al. (2012b) used a statistical imputation method to probabilistically assign fuel characteristics from the plot data to delineated stands using forest type, age, site quality, basal area, and recent fire history. This method was employed to evaluate the potential amplitude of the SRS to have a greater range of fuel characteristics (i.e., surface fuel loading and depth) than is represented by using stand averages.

Environmental variables used in each of the three modeling scenarios reflect late winter (dormant season) wildfire conditions with moderate midflame windspeeds of 6.4-km h^{-1} and a dry fuel scenario (defined in study 1). Because percentage of live shrub biomass was not sampled in the SRS forest inventory plots and could have a substantial effect on surface fire behavior predictions, we evaluated a range of percentages for plot-based predictions of surface fire behavior, including 0, 20, 50, 80, and 100 percent.

Modeled fire behavior outputs include surface reaction intensity (kW m^{-2}), rate of spread (m/min), flame length (m) and three crown fire potentials (on an index of 0–9), including (1) crown fire initiation potential (index of likelihood a surface fire will transition to crown fire), (2) crown-to-crown transmissivity potential (index of the likelihood a crown fire will spread between crowns), and (3) crown fire rate of spread potential (index of the rate of crown fire spread). FCCS outputs were mapped across the study area by plots, stand averages, and statistically-imputed stands. Surface fire behavior potential was ranked using thresholds (**Table 3**) defined by Andreu et al. (2012). Results were summarized to characterize the spatial extent and distribution of predicted fire behavior.

Although LANDFIRE and SWRA are not generally intended for fuel treatment analysis, they are often the only products managers have for strategic planning of fuel treatments. To evaluate fine-scale versus traditional coarse-scale predictions of surface fire behavior, we compared FCCS plot-based predictions of surface rate of spread and flame length to predictions made using FlamMap using LANDFIRE and SWRA fuel data under the same weather scenario (Hollingsworth et al., 2012). We compared the FlamMap raster outputs with the point-based FCCS values for the 624 plots to assess their correspondence. To reduce variability between raster cells and facilitate comparison of our plot-based data to raster data, we calculated a neighborhood average of raster cells using binary interpolation around each of the 624 plots.

4.2. Results and discussion

4.2.1. Plot-based fire behavior predictions

The plot-based assessment of surface fire rate of spread (ROS) indicates that overall hazard is low to moderate for the study area with isolated predictions of high to extreme fire behavior (**Fig. 4**). With few exceptions, the highest predicted flame lengths and rates of spread are clustered around SRS infrastructure where prescribed fire is generally not applied due to smoke prohibitions. **Table 4** presents mean and standard deviation values for the plot-based predictions of surface fire behavior and crown fire potentials. Overall, the majority of plots have low predictions of ROS (75%) with 23% in the moderate category and only 1% in the high category. The isolated plots ($n = 8$) with predicted extreme rates of spread have high shrub and/or herbaceous fuel loadings. By forest type, the highest rates of spread are predicted in young hardwood forests (5–20 years) as well as older longleaf pine – scrub oak forests (>40 years). Shrub reaction intensity is correspondingly high in both stand types.

Surface fire flame lengths are predicted to be moderate to high across all forest types with the highest flame lengths in young hardwood forests with developed shrub understories (5–20 years) and pine forests of all ages. The majority of plots (70%) have high predicted flame lengths with 20% in the moderate category, and 4% in both low and extreme categories. Plots with extreme fire hazard predictions have medium to high predicted flame lengths, tend to have very high shrub reaction intensities (>750 kW m^{-2}), and are predominantly pine or mixed pine and hardwood forests under 60 years old.

Predicted surface fire behavior varies with input percentage of live shrub biomass. As percentage of live shrubs increases, predictions of surface and crown fire behavior decline in fuelbeds containing a shrub stratum. For example, predicted rates of spread

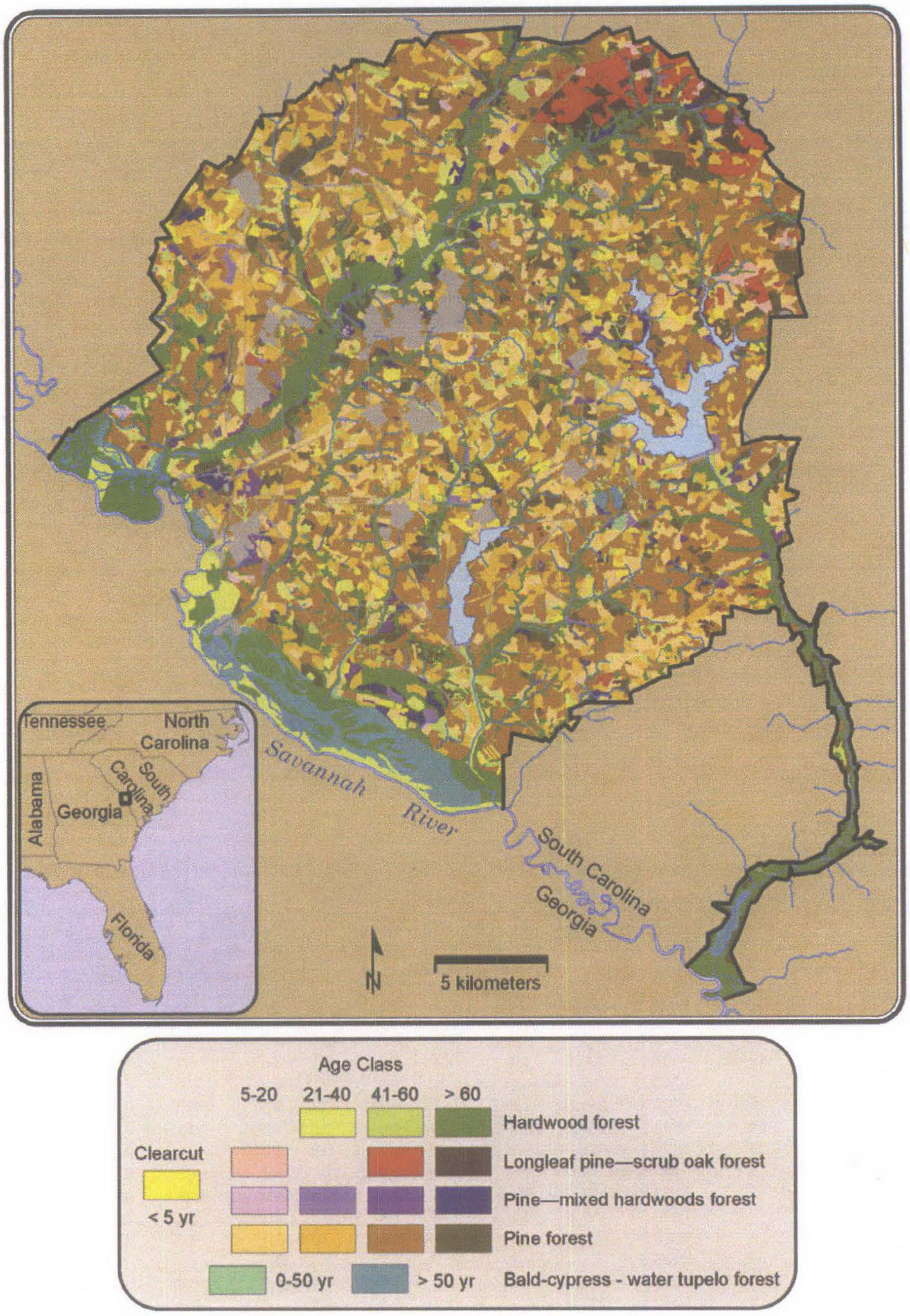

Fig. 3. Stand type and age class map of the Savannah River Site. Gray areas in the stand age class map represent non-forested areas.

Table 3
Fire hazard rating of surface fire flame length, rate of spread, and crown fire potential index.

Fire behavior rating	Rate of spread (m min^{-1})	Flame length (m)	Crown fire potentials (index 1–9)
Low	0–3.0	0–0.6	1–2
Moderate	>3.0–6.1	>0.6–1.2	2–5
High	>6.1–12.2	>1.2–2.4	5–7
Extreme	>12.2–24.4	>2.4–4.9	7–9

increase with age in longleaf pine-scrub oak forests but regardless of age are much lower with 100% live shrubs versus 0% live shrubs (Fig. 5). Percentage of live and dead vegetation was not sampled in forest inventory plots, but modeling a range of input live shrub percentages demonstrates a high sensitivity of fire predictions to this single variable. With high fuel moisture relative to standing dead fuels, live fuels can reduce the intensity and rate of spread of surface fires (Rothermel 1972). This has important implications for seasonality of burning and wildfire potential. If sites with a developed grass or shrub understory are burned in the dormant season with a high proportion of standing dead material, potential surface fire behavior is much greater and can result in higher likelihood of crown fire initiation where ladder fuels exist (Sparks et al., 2002). In addition, following herbicide treatment, a high proportion of standing dead shrub biomass would likely produce higher surface fire behavior (Gagnon and Jack 2004) and increase potential for crown fire initiation or post-fire tree mortality (Brose and Wade, 2002; Outcalt and Wade, 2004).

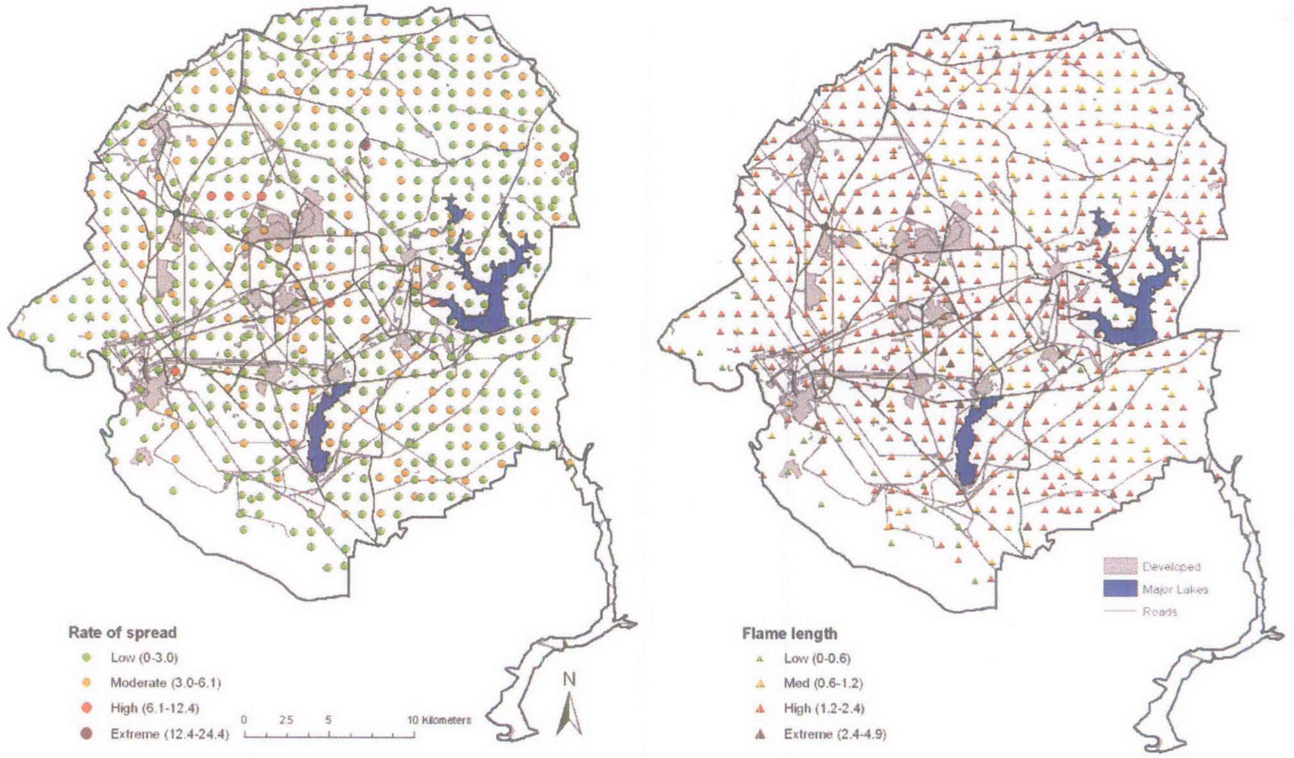

Fig. 4. Predicted rate of spread and flame length by inventory plot, classified into low, moderate, high, and extreme fire hazard categories.

Table 4
Calculated mean surface fire behavior from plot fuelbeds (reaction intensity, rate of spread, and flame length) and crown fire potentials. Standard deviations (SD) are not reported for forest type and age classes with less than 3 plots.

Forest type and age class	Plots (n)	Reaction intensity (kW m^{-2})		Rate of spread (m min^{-1})		Flame length (m)		Crown fire initiation potential (1–9)		Crown-crown transmissivity potential (1–9)		Crown fire rate spread potential (1–9)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Bald cypress – water tupelo 50+ years	5	331.4	339.6	1.9	0.9	0.7	0.5	1.7	0.5	7.2	4.0	1.1	0.4
Clear cut less than 5 years	12	493.1	330.6	1.3	1.2	0.7	0.5	3.5	3.1	1.7	2.6	0.7	0.7
Hardwood 5–20 years	2	1047.1	–	4.5	–	1.8	–	6.8	–	0.0	–	1.5	–
Hardwood 21–40 years	18	609.7	251.6	1.8	0.7	0.9	0.2	3.5	0.8	0.0	0.0	0.9	0.2
Hardwood 41–60 years	60	594.7	267.5	2.2	1.5	1.0	0.5	3.3	0.9	0.0	0.0	1.0	0.3
Hardwood 60+ years	43	679.5	526.6	2.3	2.3	1.1	0.8	3.0	0.9	0.0	0.0	0.0	0.0
Longleaf pine – scrub oak 5–20 years	2	759.4	–	1.6	–	1.0	–	5.7	–	8.2	–	1.5	–
Longleaf pine – scrub oak 21–40 years	7	1123.7	141.5	2.4	0.8	1.5	0.3	4.0	1.8	8.3	0.6	1.7	0.3
Longleaf pine – scrub oak 41–60 years	7	1035.3	91.8	4.1	1.6	1.8	0.3	5.2	0.8	7.2	3.2	1.4	0.3
Longleaf pine – scrub oak 60 + years	2	1020.2	0.1	5.4	0.1	2.1	0.0	5.1	0.4	3.7	5.3	1.2	0.2
Pine – mixed hardwood 5–20 years	1	938.8	–	3.2	–	1.5	–	9.0	–	0.0	–	1.7	–
Pine – mixed hardwood 21–40 years	3	1153.3	118.8	2.6	0.7	1.6	0.1	4.9	1.8	5.1	4.5	1.2	0.2
Pine – mixed hardwood 41–60 years	9	1067.3	197.8	2.5	0.8	1.5	0.2	3.6	0.3	6.3	2.6	1.6	0.2
Pine – mixed hardwood 60 + years	5	535.3	229.8	1.7	0.5	0.9	0.3	2.0	0.5	8.1	0.7	1.1	0.1
Pine 5–20 years	124	1237.4	302.3	2.6	1.1	1.6	0.4	6.4	1.8	8.2	2.2	2.5	0.6
Pine 21–40 years	86	1306.8	238.9	2.9	1.0	1.8	0.4	4.2	0.8	7.5	2.3	2.6	0.5
Pine 41–60 years	216	1347.3	292.3	2.6	0.7	1.8	0.4	3.8	0.5	6.5	2.8	2.7	0.6
Pine 60 + years	27	1309.2	197.3	2.7	1.0	1.8	0.3	4.0	1.1	7.2	2.5	2.8	0.6

Crown fire potentials are generally low to medium across the SRS inventory plots (Fig. 6). The majority of inventory plots (77%) are predicted to have a medium potential for crown fire initiation with 3% in the low category, 11% in the high category, and 9% in the extreme category. Potential crown-to-crown-transmissivity is high for most plots, likely due to continuous forest cover over much of the study area. However, predictions of crown fire rate of spread are confined to medium (63%) and low (37%) with no high or extreme potential values. Crown fire initiation potential is highest for those plots with high or extreme surface fire behavior predictions, and extreme values also tend to be clustered near SRS infrastructure.

Active fuels management across the study area maintains generally low fuel loads with correspondingly low potential for surface fire and crown fire behavior. Parresol et al., (2012a) demonstrate that fuel loadings are strongly correlated to forest structures; fuelbeds with midstory hardwood and shrub layers tend to have the highest fuel loads. Prescribed fire is not conducted around buildings and other sensitive infrastructure and operations at the SRS and little management takes place in DOE set-aside areas

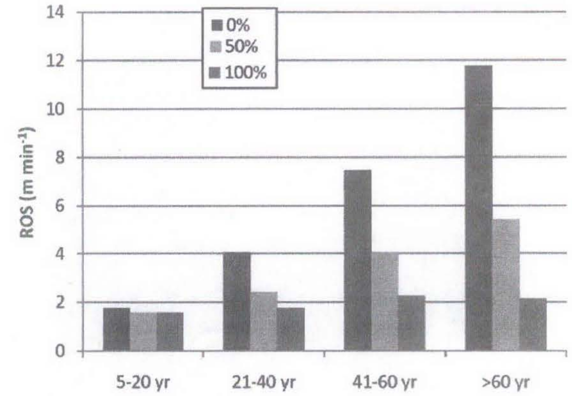

Fig. 5. Mean values for predicted rates of spread by age class by 0, 50, and 100 percent live shrub biomass in longleaf pine-scrub oak plots.

(Kilgo and Blake, 2005). Based on the plot predictions, some of the highest predictions of fire behavior tend to be clustered around infrastructure and suggest that in the absence of reduction programs, surface fuels, including litter, fine woody fuel, and dense shrub and hardwood understories, would accumulate across the study area and increase the potential for high-intensity wildfire (Marshall et al., 2008). Fuelbeds with surface fuel accumulation that results in high to extreme surface fire behavior may be applicable to untreated forest sites outside of the SRS and useful for planning fuels reduction projects (Andreu et al., 2012).

4.2.2. Stand-based fire behavior predictions

Modeled fire behavior by representative fuelbeds reveals some broad-scale differences in forest types. Predicted rates of spread are generally low across stand types with the exception of longleaf pine-scrub oak forests in the northwestern portion of the SRS (Fig. 7). Flame lengths are somewhat more variable with low flame lengths predicted for bald cypress-water tupelo forests, moderate flame lengths for hardwood forests along riparian corridors, and high flame lengths in pine forest types. Although crown-to-crown transmissivity potential is high in forest types with high percent cover, potential crown fire initiation and spread are generally low with somewhat higher potentials in longleaf pine-scrub oak and mixed pine and hardwood forest types. The fine-scale variability in inventory plots was clearly lost in this approach, and only major differences in forest types were indicated (e.g., low predicted flame lengths in bald-cypress tupelo forests located in the Southern end of the SRS and moderate rates of spread in the northeastern corner of the SRS).

Statistically imputed stand data exhibit a wider range of fire behavior predictions than the representative stand-based modeling approaches (Fig. 7). Predicted rates of spread are generally low (89%) with some isolated stands with medium (9%) to high predictions (1%). Predicted flame lengths are generally moderate (41%) to high (46%) with scattered predictions of low (11%), and extreme flame lengths (3%).

The statistical imputation of fuel characteristics to stands evaluates the potential effect a wider range of fuel characteristics would have on the forested landscape. In other words, the analysis of probabilistic surface and canopy characteristics explores the potential capacity of this landscape to support hazardous fuel conditions (Parresol et al., 2012a). Predicted fire behavior is theoretical and does not reflect actual stand conditions at any given location. In some cases, predicted fire behavior appears to be inconsistent with those predictions made by major forest type and age class. For example, portions of the bald-cypress tupelo forests are predicted to have medium to high flame lengths and high rates of spread. Similarly, the moderate rates of spread predicted for longleaf pine-scrub oak forests using the representative fuelbed approach are not reflected in the statistically imputed stand predictions. An imputation method that included, landform, management and recent disturbance history may offer a more promising technique. Direct gradient analysis employing geospatial predictive layer has been proven to be a strong predictor of plot-based data in the western United States (Pierce et al., 2009). With more stand management information (treatment type, and time since harvest and/or treatment), it may be possible to more reliably impute plot-based predictions to the SRS and similar landscapes.

Comparison of plot-based predictions of surface fire rate of spread and flame length to LANDFIRE and SWRA predictions offers a simple illustration of the differences in fine-scale versus coarse-scale predictions of surface fire behavior. There is no correlation between our plot-based predictions of rate of spread and flame length and the FlamMap output layers presented in Hollingsworth et al. (2012) ($R^2 = 0.00$ for all comparisons). Lack of correlation may result from the databases used to derive SWRA and LANDFIRE.

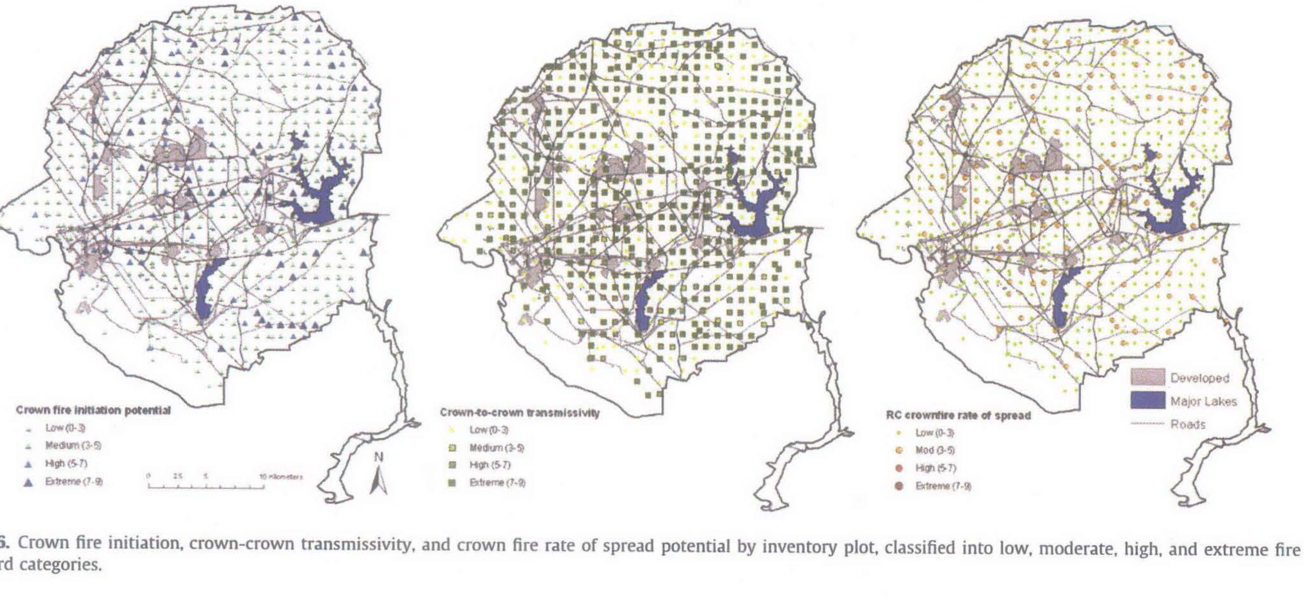

Fig. 6. Crown fire initiation, crown-crown transmissivity, and crown fire rate of spread potential by inventory plot, classified into low, moderate, high, and extreme fire hazard categories.

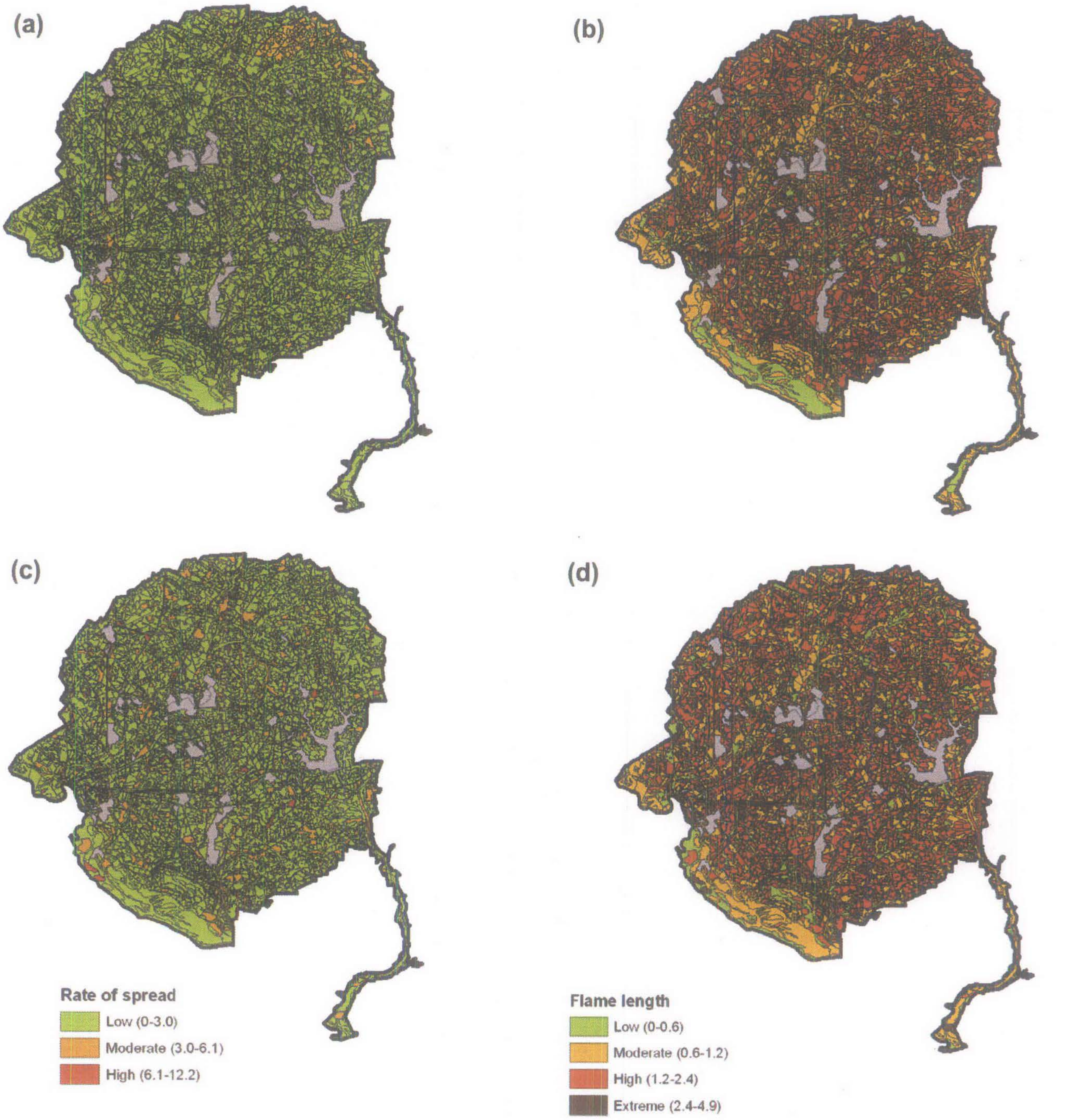

Fig. 7. Mapped predictions of (a) rate of spread by representative fuelbed, (b) flame length by representative fuelbed, (c) rate of spread by imputed stand, and (d) flame length by imputed stand.

Both systems base assessments on limited field datasets and specific years for the satellite imagery that does not coincided with the sampling period of the forest inventory plots. In addition, the majority of the study area modeled by the SWRA is represented by two of the 13 original fuel models (2, timber grass and understory and 9, long needle pine timber litter). LANDFIRE offers greater refinement in its use of the Scott and Burgan (2005) fuel models, but the plot-based fire behavior predictions demonstrates higher variability in fuels across the study area than would be captured using fire behavior fuel models.

4.3. Management implications

Plot and stand-based assessments of potential fire behavior indicate that overall hazard is low to moderate for this forested landscape. However, some localized areas of high surface fire and/or crown fire potential were identified and indicate that these areas could be prioritized for future fuel treatments. Plot-based and statistically imputed stands both suggest that the potential for high to extreme fire behavior exists for the study area. FCCS predictions of surface fire behavior are sensitive to the ratio of live-to-dead shrub biomass and suggest that this fuel characteristic is an important variable in fire hazard assessments.

Active fuels management through frequent fire, mechanical thinning, herbicide and chipping and shredding treatment appears to be effectively reducing potential fire behavior across the study area. With increasing constraints to prescribed burning through wildland-urban interface expansion and smoke management issues throughout the southeastern United States (Theobald and Romme, 2007; Marshall et al., 2008), alternative approaches to fuel reductions including biomass removal and chipping may be necessary in some locations on the SRS and in other forested landscapes of the southeastern United States (Brockway and Lewis, 1997; Heuberger and Putz, 2003; Brockway and Outcalt, 2000; Brockway et al., 2009).

Because the FCCS offers a point-based prediction of fire behavior and does not spread fire across landscapes, we evaluated two approaches to translate plot-based predictions based on measured fuels to the study landscape. The representative fuelbed approach may be useful to managers who have forest inventory data and wish to calculate stand averages to generally represent fuel characteristics and potential fire behavior across their management area. However, using mean values will fail to represent specific areas in which fuels need to be treated. The imputation method we employed demonstrated a wider range of potential fire behavior than the representative fuelbed approach but resulted in some unlikely predictions. Further development is needed to impute point-based predictions to landscapes and to translate FCCS fire behavior predictions to be used in other fire behavior prediction tools such as FlamMap and FARSITE. Many fire and fuels managers will not have access to the detailed plot information available for the SRS and would likely use the FCCS fuel treatment assessments and decision support or use representative fuelbeds to evaluate broad-scale effects of fuel treatments.

5. Conclusions

We used two case studies to introduce a relatively new approach to characterize fuels and predict potential fire behavior, fuel consumption and emissions in the upper Atlantic Coastal Plain forests of the southeastern US using the Fuel Characteristic Classification System and Consume. The case studies provide examples of common fuel treatments and their potential for reducing fire behavior and effects at fine and broad spatial scales. Results indicate fuels treatments can reduce reaction intensity, rate of spread, and flamelength by up to 58%, 57%, and 63%, respectively. Modeled potential fire behavior across the study area indicates that overall hazard is low to moderate with localized areas of high surface fire and crown fire potential.

Because many land management agencies in the southeastern US treat fuels on a one- to five-year cycle, small changes in fuelbed characteristics (i.e., fuel loading, continuity and vertical arrangement of shrubs, grasses, fine woody fuels, and litter) must be considered when predicting the effectiveness of fuel treatments in reducing fuels and potential fire behavior. Managers of Southern forests can use the FCCS in combination with Consume to represent specific fuel treatments to evaluate treatment effectiveness, develop prescriptions for wildfire hazard reduction, estimate pollutant emissions from prescribed and wildland fires, and establish restoration targets for forest structural characteristics important for species at risk (Wade and Lunsford, 1989; Brose and Wade, 2002). Furthermore, both fire behavior and fuel consumption can be predicted using the same realistic fuelbed data set. There is no scale associated with the FCCS fuelbeds, and FCCS can be used as a planning tool to represent treatments across Southern forested landscapes and evaluate fire behavior potential and effects at broad spatial scales.

Combined, the two case studies highlight the ability of the FCCS to capture fuel characteristics and differences in predicted fire behavior resulting from fuel treatments or site variability. The capacity to represent differences in the vertical arrangement and quantification of fuels enables managers to evaluate the effects and interactions of natural ecological processes and management activities and potential fire behavior and emissions.

Acknowledgements

We thank Jon Dvorak and Travis Freed for collecting and summarizing the fuels data. We thank Robert Norheim for assistance with GIS analysis and cartography. We also thank John Blake, Anne Andreu and four anonymous reviewers for their comments and suggestions that improved the manuscript. Funding for this work was provided by US Department of Energy-Savannah River Operations Office through the US Forest Service-Savannah River under Interagency Agreement DE-AI09-00SR22188, and the US Forest Service Pacific Northwest Research Station.

References

Agee, J.K., Skinner, C.N., 2005. Basic principles of forest fuel reduction treatments. For. Ecol. Manage. 211, 83–96.

Anderson, Hal. E., 1982. Aids to determining fuel models for estimating fire behavior. GTR-INT-122. US Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT.

Andreu, A.G., Shea, D., Parresol, B.R., Ottmar, R.D., 2012. Evaluating fuel complexes for fire hazard mitigation planning in the southeastern United States. For. Ecol. Manage. 273, 4–16.

Andrews, P.L., 1986. BEHAVE: fire behavior prediction and fuel modeling system – BURN Subsystem, Part 1. GTR-INT-194. US Forest Service Intermountain Research Station, Ogden, UT.

Arroyo, L.A., Pascual, C., Mananera, J.A., 2008. Fire models and methods to map fuel types: the role of remote sensing. For. Ecol. Manage. 256, 1239–1252.

Brockway, D.G., Lewis, C.E., 1997. Long-term effects of dormant-season prescribed fire on plant community diversity, structure and productivity in a longleaf pine wiregrass ecosystem. For. Ecol. Manage. 96, 167–183.

Brockway, D.G., Outcalt, K.W., 2000. Restoring longleaf pine wiregrass ecosystems: hexazinone application enhances effects of prescribed fire. For. Ecol. Manage. 137, 121–138.

Brockway, D.G., Outcalt, K.W., Estes, B.L., Rummer, R.B., 2009. Vegetation response to midstory mulching and prescribed burning for wildfire hazard reduction and longleaf pine (*Pinus palustris* Mill.) ecosystem restoration. Forestry 82, 299–314.

Brockway, D.G., Outcalt, K.W., Tomczak, D.J., Johnson, E.E., 2005. Restoration of Longleaf Pine Ecosystems, GTR-SRS-83. US Forest Service, Southern Research Station, Asheville, NC.

Brose, P., Wade, D., 2002. Potential fire behavior in pine flatwood forests following three different fuel reduction techniques. For. Ecol. Manage. 163, 71–84.

Brown, J.K., 1974. Handbook for inventorying downed woody material. GTR-INT-16. US Forest Service, Intermountain Research Station, Ogden, UT.

Buckley, D.D., Krieter, C.D., Sabourin, K., 2006. Southern Wildfire Risk Assessment: Final Report. Sanborn Map Company, Colorado Spring, CO.

Canfield, R.H., 1941. Application of the line interception method in sampling range vegetation. J. For. 39, 388–394.

Cottam, G., Curtis, J.T., 1956. The use of distance measures in phytosociological sampling. Ecology 37, 451–460.

Cox, A.C., Gordon, D.R., Slapcinsky, J.L., Seamon, G.S., 2004. Understory restoration in longleaf pine sandhills. Nat. Areas J. 24, 4–14.

Davis, L.S., Cooper, R.W., 1963. How prescribed burning affects wildfire occurrence. J. For. 61, 915–917.

Drewa, P.B., Platt, W.J., Barry, E., 2002. Fire effects on resprouting of shrubs in headwaters of southeastern longleaf pine savannas. Ecology 83, 755–767.

Ferguson, E.R., 1961. Effects of prescribed fires on understory stems in pine-hardwoods stands of Texas. J. For. 59, 356–359.

Fettig, C.J., Klepzig, K.D., Billings, R.F., Munson, A.S., Nebeker, T.E., Negrón, J.F., Nowak, J.T., 2007. The effectiveness of vegetation management practices for prevention and control of bark beetle infestations in coniferous forests of the western and southern United States. For. Ecol. Manage. 238, 24–53.

Freeman, J.E., Jose, S. 2009. The role of herbicide in savanna restoration: effects of shrub reduction treatments on the understory and overstory of a longleaf pine flatwoods. For. Ecol. Manage., 978–986.

Frost, C.C., 1993. Four centuries of changing landscape patterns in the longleaf pine ecosystem. In: Herman, S.M. (Ed.), Proceedings of the 18th Tall Timbers Fire Ecology Conference. Tall Timbers Research Station, Tallahassee, FL, pp. 17–43.

Gagnon, J.L., Jack, S.B., 2004. A comparison of the ecological effects of herbicide and prescribed fire in a mature longleaf pine forest: response of juvenile and overstory pine. In: Connor, Kristina F. (Ed.), Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS-71. US Forest Service, Southern Research Station, Asheville, NC.

Glitzenstein, J.S., Platt, W.J., Streng, D.R., 1995. Effects of fire regime and habitat on tree dynamics in north Florida longleaf pine savannas. Ecol. Monogr. 65, 441–476.

Glitzenstein, J.S., Streng, D.R., Achtemeier, G.L., Naeher, L.P., Wade, D.D., 2006. Fuels and fire behavior in chipped and unchipped plots: implications for land management near the wildland/urban interface. For. Ecol. Manage. 236, 18–29.

Glitzenstein, J.S., Streng, D.R., Wade, D.D., 2003. Fire frequency effects on longleaf pine (*Pinus palustris*, P. Miller) vegetation in South Carolina and northeast Florida, USA. Nat. Area. J. 23, 22–37.

Haywood, J.D., 2007. Restoring fire-adapted forested ecosystems-research in longleaf pine on the Kisatchie National Forest. US Forest Service Southern Research Station, PSW-GTR-203. Asheville, NC.

Haywood, J.D., 2009. Eight years of seasonal burning and herbicidal brush control influence sapling longleaf pine growth, understory vegetation, and the outcome of an ensuing wildfire. For. Ecol. Manage. 258, 295–305.

Heuberger, K.A., Putz, F.E., 2003. Fire in the suburbs: ecological impacts of prescribed fire in small remnants of longleaf pine (Pinus palustris) sandhill. Restor. Ecol. 11, 72–81.

Hiers, J.K., O'Brien, J.J., Mitchell, R.J., Grego, J.M., Loudermilk, E.L., 2009. The wildland fuel cell concept: an approach to characterize fine-scale variation in fuels and fire in frequently burned longleaf pine forests. Int. J. Wildlife Fire 18, 315–325.

Hollingsworth, L.T., Kurth, L.L., Parresol, B.R., Ottmar, R.D., Prichard, S.J., 2012. A comparison of geospatially modeled fire behavior and management utility of three data sources in the southeastern United States. For. Ecol. Manage. 273, 43–49.

Kilgo, J., Blake, J. (Eds.), 2005. Ecology and Management of a Forested Landscape: Fifty Years on the Savannah River Site. Island Press, Covelo, CA.

Marshall, D.J., Wimberly, M., Bettinger, P., Stanturf, J., 2008. Synthesis of knowledge of hazardous fuels management in loblolly pine forests. GTR-SRS-110, US Forest Service Southern Research Station. Asheville, NC.

Martin, G.G., 1988. Fuels treatment assessment-1985 fire season in region 8. Fire Manage. Notes 49, 21–24.

Moore, E.B., Smith, G.E., Little, S., 1955. Wildfire damage reduced on prescribe-burned areas in New Jersey. J. For. 53, 339–341.

Noss, R.F., 1989. Longleaf pine and wiregrass: keystone components of an endangered ecosystem. Nat. Area. J. 9, 211–213.

Ottmar, R.D., Miranda, A., Sandberg, D.V., 2009. Characterizing sources of emissions from wildland fires. In: Bytnerowicz, Andrzej, Arbaugh, Michael, Michael, R.A., Riebau, Allen, Andersen, Christian (Eds.), Wildland fires and air pollution. Chapter 3. Developments in Environmental Science Series, Volume 8. Elsevier, Amsterdam.

Ottmar, R.D., Prichard, S.J., Anderson, G.A., 2005. Consume 3.0. <http://www.fs.fed.us/pnw/fera/research/smoke/consume/index.shtml>.

Ottmar, R.D., Sandberg, D.V., Riccardi, C.L., Prichard, S.J., 2007. An overview of the Fuel Characteristic Classification System – Quantifying, classifying, and creating fuelbeds for resource planning. Can. J. For. Res. 37, 2383–2393.

Outcalt, K.W., Sheffield, R.M., 1996. The Longleaf Pine Forest: Trends and Current Conditions. Resource Bulletin SRS-9. USDA Forest Service, Southern Research Station, Asheville, NC.

Outcalt, K.W., Wade, D.D., 2004. Fuels management reduces tree mortality from wildfires in Southeastern United States. South. J. Appl. For. 28, 28–34.

Parresol, B.R., Blake, J., Thompson, A.J., 2012a. Ecological processes and land management history structure surface hazardous wildland fuel relationships within a contiguous forest landscape in the southeastern USA. For. Ecol. Manage. 273, 29–42.

Parresol, B.R., Scott, J.H., Andreu, A., Prichard, S., Kurth, L., 2012b. Developing custom fire behavior fuel models from ecologically complex fuel structures for upper Atlantic Coastal Plain forests. For. Ecol. Manage. 273, 50–57.

Peterson, D.L. Johnson, M.C., Agee, J.K., Jain, T.B., McKenzie, D., Reinhardt, E.R. 2005. Forest structure and fire hazard in dry forests of the western United States. USDA For. Serv. Gen. Tech. Rep. PNW-GTR-628.

Pierce Jr., K.B., Ohmann, J.L., Wimberly, M.C., Gregory, M.J., Fried, J.S., 2009. Mapping wildland fuels and forest structure for land management: a comparison of nearest-neighbor imputation and other methods. Can. J. For. Res. 39, 1901–1916.

Provencher, L., Herring, B.J., Gordon, D.R., Rodgers, H.L., Tanner, G.W., Hardesty, J.L., 2001. Longleaf pine and oak responses to hardwood reduction techniques in fire-suppressed sandhills in northwest Florida. For. Ecol. Manage. 148, 63–77.

Reiner, A.L., Vaillant, N.M., Fites-Kaufman, J., Dailey, S.N., 2009. Mastication and prescribed fire impacts on fuels in a 25-year-old ponderosa pine plantation, southern Sierra Nevada. For. Ecol. Manage. 258, 2365–2372.

Rollins, M.G., 2009. LANDFIRE: a nationally consistent vegetation, wildland fire, and fuel assessment. Int. J. Wildlife Fire 18, 235–249.

Rothermel, R.C., 1972. A mathematical model for predicting fire spread in wildland fuels. INT-RP-115. US Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT.

Sackett, S.S., 1975. Scheduling prescribed for hazard reduction in the Southeast. J. For. 73, 143–147.

Sandberg, D.V., Riccardi, C.L., Schaaf, M.D., 2007a. Fire potential rating for wildland fuelbeds using the Fuel Characteristic Classification System. Can. J. For. Res. 37, 2456–2463.

Sandberg, D.V., Riccardi, C.L., Schaaf, M.D., 2007b. Reformulation of Rothermel's wildland fire behaviour model for heterogeneous fuelbeds. Can. J. For. Res. 37, 2438–2455.

Scott, J.H., Burgan, R.E., 2005. Standard fire behavior fuel models: a comprehensive set for use with Rothermel's surface fire spread model. RMRS-GTR-153. US Forest Service Rocky Mountain Research Station, Fort Collins, CO.

Sparks, J.C., Masters, R.E., Engle, D.M., Bukenhofer, G.A., 2002. Season of burn influences fire behavior and fuel consumption in restored shortleaf pine-grassland communities. Restor. Ecol. 10, 714–722.

Theobald, D.M., Romme, W.H., 2007. Expansion of the US wildland-urban interface. Landscape Urban Plan 83, 340–354.

Tian, H., Chen, G., Liu, M., Zhang, C., Sun, G., Lu, C., Xu, X., Ren, W., Cappela, A., 2010. Model estimates of net primary productivity, evapotranspiration, and water use efficiency in the terrestrial ecosystems of the southern United States during 1895–2007. For. Ecol. Manage. 259, 1311–1327.

Van Lear, D.H., Carroll, W.D., Kapeluck, P.R., Johnson, R., 2005. History and restoration of the longleaf pine-grassland ecosystem: implications for species at risk. For. Ecol. Manage. 211, 150–165.

Wade, D.D., 1993. Thinning young loblolly-pine stands with fire. Int. J. Wildlife Fire 3, 169–178.

Wade, D.D., Lunsford, J.D., 1989. A guide for prescribed fire in southern forests. US Forest Service, Southern Region Technical Publication R8-TP-11, Atlanta, GA.

Waldrop, T.A., Phillips, R.A., Simon, D.A., 2009. Fuels and predicted fire behavior in the southern Appalachian Mountains after fire and fire surrogate treatments. For. Sci. 56, 32–45.

Waldrop, T.A., White, D.L., Jones, S.M., 1992. Fire regimes for pine-grassland communities in the southeastern United States. For. Ecol. Manage. 47, 195–210.

Waldrop, T.A., van Lear, D.H., Lloyd, T.F., Harms, W.R., 1987. Long term studies of prescribed burning in loblolly pine forests of the Southeastern Coastal Plain. GTR-SE-45. US Forest Service, Southeastern Forest Experiment Station, Asheville, NC.

Zhang, Y., He, H.S., Yang, J., 2008. The wildland-urban interface dynamics in the southeastern US from 1990 to 2000. Landscape Urban Plan 85, 155–162.

Zwicker, S.M., Walters, J.R., 1999. Selection of pines for foraging by red-cockaded woodpeckers. J. Wildlife Manage. 63, 843–852.